On Cutting Tool Resource Management

Ana Esther Bonilla Hernández
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To my family
Acknowledgements

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Ana Esther Bonilla Hernández

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Nyckelord: Avverkningshastighet; CAM programmering; Hållbarhet; Lean; Optimering; Skärdatal; Tillverkning; Verktygslivslängd; Verktygsslitage; Verktygsutnyttjande


Två olika kombinationer av skärdatal kan ge samma MRR, men verktygets livslängd och bearbetningskostnaden kommer att vara annorlunda. Svårigheten är därför att välja skärdatal som tar hänsyn till alla mål. I avhandlingen presenteras en ny algoritm för analys och effektivt val av skärdatal som ger maximal avverkningshastighet, maximalt verktygsutnyttjande och minimal bearbetningskostnad. Den utvecklade algoritmen förkortar tiden som behövs för skärdatavalet och de nödvändiga stegen längs programutvecklingen.

Vidare kommer framåtblickande företag att sträva efter hållbarhet i sina tillverkningsprocesser. Viktiga mål som måste beaktas vid hållbarhetsarbete har identifierats och studerats. Dessutom presenteras en teoretisk studie för att uppskatta energianvändningen, koldioxidutsläpp och vattenförbrukning vid framställning av ett arbetssycke.
Abstract

Title: On cutting tool resource management

Keywords: CAM programming; Cutting data; Lean; Manufacturing; Material Removal Rate; Optimization; Tool life; Tool utilization; Tool wear; Sustainability


The search for increased productivity and cost reduction in machining can be interpreted as desire to increase the Material Removal Rate, \( MRR \), and maximize the cutting tool utilization. The CNC process is complex and involves numerous constraints and parameters; ranging from tolerances to machinability. A well-managed preparation process creates the foundation for achieving a reduction in manufacturing errors and machining time. Along the preparation process of the NC-program, two different studies have been performed and are presented in this thesis. One study examined the CAM programming process from the Lean perspective. The other study includes an evaluation of how the cutting tools are used in terms of \( MRR \) and tool utilization.

Two distinct combinations of cutting data might provide the same \( MRR \). However, the tool life and machining cost can be different. Therefore, selection of appropriate cutting parameters that best meet all these objectives is challenging. An algorithm for analysis and efficient selection of cutting data for maximal \( MRR \), maximal tool utilization and minimal machining cost has been developed and is presented in this work. The presented algorithm shortens the time dedicated to the optimized cutting data selection and the needed iterations along the program development.

Furthermore, the objectives that need to be considered during the estimation of the manufacturing processes sustainability have been identified. In addition, this thesis also includes a theoretical study to estimate energy use, \( \text{CO}_2 \)-footprint and water consumption during the manufacture of a workpiece, which can be invaluable for companies in their search for sustainability of their manufacturing processes.
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Paper A. Lean study of the CAM Programmer’s role during the CAM Programming Process

Accepted for publication in the 14th International Conference on High Speed Machining, April 2018 – Authors: Ana Esther Bonilla Hernández, Tomas Beno

Author’s contribution: Principal and corresponding author. Interviewed CAM Programmers. Developed detailed CAM programming work flow. Analyzed CAM programming work flow from Lean perspective and complied findings. Wrote the main manuscript text.

Paper B. Analysis of tool utilization from Material Removal Rate perspective


Author’s contribution: Principal and corresponding author. Analyzed CNC program. Compiled results and analyzed data. Wrote the main manuscript text and presented paper orally at the conference.

Paper C. Integrated optimization model for cutting data selection based on maximal MRR and tool utilization in continuous machining operations


Author’s contribution: Principal and corresponding author. Developed and analyzed the presented model. Wrote the main manuscript text.
Paper D. Integrated Optimization of tool utilization in drilling operations

Submitted for publication in an International Scientific Journal, January 2018 – Authors: Ana Esther Bonilla Hernández, Markus Hartikainen, Tomas Beno

Author’s contribution: Principal and corresponding author. Studied and analyzed the theoretical background. Developed and analyzed the methodology to optimize the cutting data selection for a drilling operation. Study of the influence of the decision variables. Wrote the main manuscript text.

Paper E. On cost optimization in CAM systems for drilling operations

Submitted for publication in an International Scientific Journal, January 2018 – Authors: Ana Esther Bonilla Hernández, Tomas Beno

Author’s contribution: Principal and corresponding author. Studied and analyzed the theoretical background. Developed and analyzed the methodology to manage cutting tools in an optimized manner, including a theoretical numerical example. Wrote the main manuscript text.

Paper F. Energy and cost estimation of a feature-based machining operation on HRSA


Author’s contribution: Principal and corresponding author. Compiled results and analyzed data. Wrote the main manuscript text and presented paper orally at the conference.
Nomenclature

Variables:
\( a_p \) Depth of cut [mm]
\( \alpha, \beta, \gamma, C_t \) Taylor tool life equation constants
\( C \) Constant that represents the cutting speed for which the tool life is one minute
\( C_{lab} \) Labour cost [$/h]
\( C_m \) Machining cost [$]
\( C_{mac} \) Machine cost [$/h]
\( C_{tool} \) Tool cost [$/cutting tool]
\( d \) Drill diameter [mm]
\( D_0 \) Diameter of the workpiece before machining operation [mm]
\( D_1 \) Diameter of the workpiece after machining operation [mm]
\( D_c \) Drill diameter/machined diameter [mm]
\( d_o \) Diameter [mm]
\( f \) Feed per revolution [mm/rev]
\( f_{mec} \) Maximal feed that the tool can sustain due to mechanical properties [mm/rev]
\( f_{min} \) Minimum recommended feed [mm/rev]
\( f_t \) Feed per tooth [mm]
\( h \) Feed distance [mm]
\( K_p \) Primary cutting edge angle [°]
\( K_r' \) Secondary cutting edge angle [°]
\( k_c \) Specific cutting force [N/mm²]
\( L \) Hole depth [mm]
\( L_z \) Machined length of the workpiece [mm]
\( M \) Number of holes machined per cutting tool [-]
\( MRR_{min} \) Minimum recommended \( MRR \) [cm³/min]
\( N \) Number of holes achieved by one drill bit [-]
\( N_h \) Number of holes in the workpiece [-]
\( N_t \) Number of cutting tools [-]
\( n \) Spindle speed [rpm]
\( n_{max} \) Maximal spindle speed [rpm]
\( n_t \) Number of flutes or teeth per drill [-]
\( \eta \) Machine efficiency (in terms of power) [-]
\( P_c \) Required cutting power [kW]
\( P_{max} \) Maximal cutting power provided by the machine [kW]
$P_t$ Cutting tool price [\$]
$P_{th}$ Tool holder price [\$]
$q_l$ Specified MRR-level [cm³/min]
$r_a$ Average surface roughness on machined surface [µm]
$r_{max}$ Maximal surface roughness [µm]
$r_c$ Nose radius of the cutting tool [mm]
$r, r^*$ Residue/ reminder [no. of holes]
$T$ Tool life [min]
$T_{th}$ Tool holder life [no. of tools]
$t_{eng}$ Engagement time for each hole [min]
$t_k$ Machining time for the k:th operation [min]
$t_m$ Effective machining/cutting time [min]
$t_{mov}$ Time to move from one hole to the next [min]
$t_{retr}$ Retract time for each hole [min]
$t_{s-s}$ Start and stop time [min]
$t_{tch}$ Tool change time [min]
$t_{tot}$ Total operation time [min]
$V$ Volume of material removed [cm³]
$V_B$ Flank wear [mm]
$V_{Bn}$ Tool wear criteria limit [mm]
$v_c$ Cutting speed [m/min]
$v_{c_{therm}}$ Maximal cutting speed that the tool can sustain due to thermal properties [m/min]
$v_{c_{min}}$ Minimum recommended cutting speed [m/min]
$v_f$ Feed speed or penetration rate [mm/min]
$\theta$ Drill point angle [°]
$\gamma_0$ Rake angle [°]
$\Delta Z$ Length of the movement along the piece in Z axis [mm]

Abbreviations:
APT Automatically Programmed Tool
BUE Built-up-edge
CAD Computer Aided Design
CAE Computer Aided Engineering
CAM Computer Aided Manufacturing
CAPP Computer Aided Process Planning
CIM Computer Integrated Manufacturing
CL Cutter Location
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>DM</td>
<td>Decision Maker</td>
</tr>
<tr>
<td>ETL</td>
<td>Expected tool life [min]</td>
</tr>
<tr>
<td>HRSA</td>
<td>Heat resistant super alloy</td>
</tr>
<tr>
<td>HSS</td>
<td>High-speed steel</td>
</tr>
<tr>
<td>M</td>
<td>Manufacturing stage</td>
</tr>
<tr>
<td>MRR</td>
<td>Material Removal Rate ([cm^3/\text{min}])</td>
</tr>
<tr>
<td>NC</td>
<td>Numerical Control</td>
</tr>
<tr>
<td>PLM</td>
<td>Product Lifecycle Management</td>
</tr>
<tr>
<td>PM</td>
<td>Pre-manufacturing stage</td>
</tr>
<tr>
<td>PU</td>
<td>Post-use stage</td>
</tr>
<tr>
<td>RTL</td>
<td>Remaining tool life [% of ETL]</td>
</tr>
<tr>
<td>S</td>
<td>Non-empty feasible region or Feasible set</td>
</tr>
<tr>
<td>SCL</td>
<td>Spiral cutting length [m]</td>
</tr>
<tr>
<td>U</td>
<td>Usage stage</td>
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<tr>
<td>UTL</td>
<td>Utilized tool life [% of ETL]</td>
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I. INTRODUCTORY CHAPTERS

1 Introduction

Manufacturing of products starts with raw materials that are subject to several processes, such as casting, bulk-deformation, sheet-metal-forming, polymer-processing, machining and joining processes [1]. Each of these processes will add some value to the initial raw material.

One of the manufacturing processes used to produce the final shape of a product is metal cutting. This type of processing is in continue development together with the development of materials, computers or sensors [2].

When manufacturing metal products, cutting processes such as turning, milling or drilling will add a considerable value to the products [3]. These processes aim to manufacture products with “high degree of production efficiency, i.e. at the quality level and within the period of time desired, and at appropriate cost” [3].

Manufacturing companies look for high productivity, which in the case of machining can be translated into Material Removal Rate, \(MRR\). This is the amount of material that is removed by a cutting tool during a defined period of time. In the search of higher productivity, the CAM Programmer might select cutting tools from a higher cutting speed or feed rate perspective. However, the \(MRR\) value achieved might not be improved. Such results frequently appear when the combination of the parameters that constitutes the \(MRR\) is overlooked. Thus, one rarely analyses the real \(MRR\) as a combination of parameters, but rather as one of the three (cutting speed, feed rate and depth of cut) separately.

Concerning the total amount of material that a cutting tool can remove during its lifetime, the cutting parameters must be chosen with care. Particularly since different variables will have different impact on the tool life [4].

Every company that wants to be competitive in the global market needs to reduce the time to market for new products [5]. Furthermore, they need to strive to satisfy every customer and their individual demands with customized products. Despite the increase in variety and small volumes companies must still
aim for products of high quality and cost effective production [6]. To accomplish this, the use of computer integrated technologies has increased over the years, including Computer Aided Design, CAD, Computer Aided Manufacturing, CAM, and Computer Aided Engineering, CAE, to support design, manufacturing and business operations [7].

Two of the main driving forces for development efforts in machining are component integrity and process robustness. The goal is to obtain the best possible properties on the generated surfaces while maintaining high productivity and high process efficiency combined with low cost and preserved robustness.

Many companies look for ways to convert their tacit knowledge into models that can be stored, shared and reused in new projects [8]. The outcome sought in such strategies, is the possibility to reuse information and knowledge in future projects, thereby reducing lead time in the introduction and development of new products. At the same time, the company can gain from operator independency and avoid recurrence of manufacturing mistakes [9].

The focus of this work is on companies with low product volumes that produce complex parts, such as aerospace engine companies, rather than e.g. automotive industry. A large part of their development time for new products is invested into the generation of Computer Numerical Control, CNC, programs to control the machine tools used in the different manufacturing processes. In modern CAM systems, there is still a lack of guidance for the CAM Programmer to define the best possible cutting data for the workpiece and the points when the tool needs to be changed with regard to tool life and tool utilization [10].

The work presented in this thesis is oriented towards the machining of difficult-to-machine materials commonly used in the aerospace industry. These are Heat Resistant Super Alloys, HRSA, such as Ni-base alloys. One of the primary working conditions, which the different components are exposed to, is elevated temperatures. Hence, the need for using materials that will retain their strength at high temperatures [11]. These materials also have properties, such as low machinability, which unfortunately results in the difficulty to machine them.

In this context, it is important to mention the crucial role that the cutting tools will play during the machining operations. The selection of the correct cutting tool and the appropriate cutting process will set the basis not only for an efficient process, but will also ensure that the geometrical and surface requirements of the component can be achieved [12].
INTRODUCTION

The cutting tools needed for machining hard-to-machine materials represent a significant percentage of the total cost [13]. The cutting tools used to machine difficult to machine materials such as Nickel-based super alloys exhibit high wear rates, resulting in a large number of tools needed to machine each component.

1.1 Scope and aim of the study

The overarching scope of this work is to study the integration of advanced technology data during the preparation of resources needed for the operation of advanced machining systems and how to make accessible the reutilization of tacit knowledge during the programming procedures of numerically controlled machine tools.

The aim of this work is to investigate the CAM process in order to identify possible inefficiencies in today’s work flow that could be improved. The outcome of this work will facilitate the development of new knowledge and algorithms to make technology data more accessible in a CAM system and to support the CAM Programmer with optimized cutting data, with respect to productivity, tool wear, tool utilization and manufacturing cost. In addition, other sustainability objectives are suggested to take into account during the development stage of NC programs.

1.2 Limitations

The work presented here has several limitations in its scope. Firstly, only one company was investigated for the study of the CAM programming process, as representative of the aerospace industry. Secondly, the CNC program of one component was selected for evaluation of the cutting tool utilization in current production. Thirdly, longitudinal turning was selected as the machining operation for which to investigate cutting tool utilization and to develop the presented algorithm for analysis and selection of cutting data. Fourthly, a drilling operation was selected for the investigation and further development of the cutting data selection algorithm. In addition, only three different criteria were considered for the multi-objective selection process. Lastly, the energy use, the cost, the water consumed and the CO2-footprint were selected to estimate the sustainability of the machining operations during the production of a workpiece.
1.3 Research questions

To be competitive, every company has the need to reduce waste and keep focus on the value adding activities [14]. To get an understanding of the processes and the efficiency in the utilization of the different resources available, the research questions investigated in this thesis are presented below:

1. How do CAM Programmers conduct the CAM programming process?
2. What kinds of inefficiencies exist in the CAM programming process from the Lean perspective?
3. What is the role of the CAM Programmer in the CAM programming process?

The selected cutting parameters (cutting speed, feed and depth of cut) will establish, not only the amount of material removed and its rate, but also the tool wear. Introduction of tool wear limitations into early phases of the CAM programming work flow can result in a more cost effective product development process and consequently more effective production. Thus, the following research questions:

4. How are the cutting tools used in production with respect to tool utilization?
5. How can the cutting data selection be optimized during the tool path generation?
6. How to select the cutting data for a drilling operation that will assure maximal MRR, maximal UTL and minimum C_m?

Furthermore, other main objectives that can be added into the optimization of the cutting data selection are the ones related to sustainability of the workpiece manufacture:

7. Which objectives can be considered to estimate the sustainability of a manufacturing process?
8. How to estimate, in a simple but realistic manner, the energy use, the CO2-footprint and the water use during the manufacturing of a workpiece?
1.4 Research approach

The research work has been divided into different main tasks, see a visual representation of the investigated areas in Figure 1, where the improvement of tool utilization is plotted against the research time dedicated for the work.

In order to understand the CAM programming work flow and how CAM Programmers are involved in the work flow, an investigation of the CAM programming process from the Lean perspective was performed. This was done by semi-structured interviews with CAM Programmers. This study provided an understanding of how the CAM Programmers are organized, i.e., how they work and how they relate to the different projects they are involved in.

A solid foundation and understanding of how the part geometry data at different stages of the CAM programming work flow is related to the cutting tool technology data was searched. Thus an existing CNC program for machining advanced aero engine component of HRSA materials was analyzed with respect to MRR and cutting tool utilization. Insights into the current situation in the CAM programming environment were gained through this case study.

An algorithm for efficient selection of cutting data with focus on maximal MRR and tool utilization, specific for longitudinal turning operations, has been developed. This algorithm provides the structure for how to integrate advanced technology data in the CAM programming work flow based on the part geometry data and cutting tool technology information.

Figure 1: Visual representation of the areas investigated over time.
Further development of the algorithm, specifically for drilling operations, has been carried out. Here, maximal MRR and tool utilization were the initial focus. However, further development allowed the integration of a third criterion, the machining cost. This algorithm can ease the CAM programming process by providing the optimal cutting data for each operation.

Finally, a theoretical study of the energy used, the cost, the water consumed and the CO2-footprint of the machining processes required for the manufacture of a workpiece was performed. This methodology, which includes both turning and drilling operations, present the initial steps required to explore the sustainability of the machining processes.

1.5 Thesis outline

This thesis is outlined as follows:

Section I is dedicated to the introductory chapters (Chapters 2-4). A brief historical background and short description of CAM programming, Lean principles, sustainable manufacturing and optimization fundamentals are presented. This section also presents the merger of the tool life equation and MRR by superimposing them.

Section II is dedicated to the investigation chapters (Chapters 5-9). First a study of the CAM programming process based on investigations performed within an aerospace industry company is presented. The study is conducted from the Lean perspective and also proposes improvements to the investigated work flow. Next, the findings of a second study with focus on how the cutting tools are used in production are presented. Furthermore, this section also presents a developed algorithm for cutting data selection based on maximal MRR and tool utilization, specific for longitudinal turning operations. Then, further development of the algorithm, taking into account more criteria and specific for drilling operation is presented. Lastly, the methodology to estimate the energy use, CO2-footprint and water required in the manufacture of a workpiece is presented.

Section III is dedicated to the conclusive chapters (Chapters 10-12). An analysis of the findings that help answer the research questions is presented in this section, together with the conclusions, a short discussion and further work.

Finally, Section IV includes all the appendices and appended papers.
2 Background

Machining and manufacturing systems have been subject to a magnificent evolution from using tools of stone, wood or bone to the development of new materials, new tools, computer integrated machining or computer simulation [1].

2.1 Historical development of machining

It is possible to set the origin of Machining and Manufacturing systems to the period before 4000 B.C. with the use of tools of stone, wood or bone among other materials [1]. A brief history of machining and the development of CAD/CAM is presented as follows to provide information about important milestones over the last centuries, to understand their origins and interactions [1, 15-17].

During the 18th century, the development of drilling and turning operations took place as well as the screw-cutting lathe among others.

Continuous development during the 19th century of shaping and milling operations, brought among others, the development of the turret lathe or the universal milling machine.

The 20th century brought developments on materials which allowed also new tools, new lathes and automatic machines, automatic control, ultraprecision machining, computer integrated machining, milling and turning centers, and computer simulation and optimization among others.

During the 1950s, the Automatically Programmed Tool system, APT, was developed. This allowed the definition of the part geometry, the tool, the machining parameters, the path that the tool will follow along the process and other features in order to combine advanced data processing and Numerically Controlled, NC, machine tools to produce complex parts [16]. Therefore, the purpose of the APT System is to allow the part programmer to write the instructions in a high level language rather than in a detailed numerical code [18].
Further improvements in computational technology and computational speed helped the development of CAD, CAM and CAE. This allowed the automatic programming by the computer, and simplified the work of the part programmer.

A NC part programming was created during the 1960s as the first prototype of an application to combine CAD and CAM. At the same time, machine oriented controls were developed.

During the 1970s, thanks to the development of computer drafting, computer graphics and the underlying mathematic foundations, this technology continued to grow and expand. By using NC, instead of following a physical part, the servomechanisms obtained the desired position information. This included one number for each controlled axis and another number representing time, through a punched tape or similar. Also the machine controls were continuously developed into NC control systems (second generation) and NC modular systems (third generation).

New theories and algorithms were developed during the 1980s. Limitations in hardware and software capabilities were solved and brought to the market with improved features. CNC controls were developed for editing and operating with the possibility of manual input and diagnostics. The increased flexibility and versatility also allowed to have simpler clamping parts.

Management capabilities of CAD/CAM were developed during the 1990s. A better and accurate integration of CAD/CAM systems was achieved. The development of the virtual factory was started at the same time as the cost of hardware and software decreased.

Development of features such as modeling and computing continued during the 21st century. Enabling the continuous development of integrated manufacturing systems, intelligent and sensor-based machines, telecommunications and global manufacturing networks, virtual environments and high-speed information systems, thus enabling the forth industrial revolution [19]. According to Lasi, et.al, the vision of future production “contains modular and efficient manufacturing systems and characterizes scenarios in which products control their own manufacturing process” [20].

### 2.2 Automation and Numerical Control

Automation can be defined as “the process of enabling machines to follow a predetermined sequence of operations with little or no human intervention and
using specialized equipment and devices that perform and control manufacturing processes and operations” [1]. Therefore, the implementation of automation can help any company to reduce costs, decrease production cycle times, decrease the amount of manual tasks and increase process robustness and product quality, which justify the use of automation [21].

Numerical control, NC, can be defined as “a form of programmable automation in which the mechanical actions of a machine tool or other equipment are controlled by a program containing coded alphanumeric data” [21].

New product requirements demand a greater complexity of the workpieces with smaller and smaller tolerances. The achievable accuracy, repeatability and precision of certain operations cannot be accomplished without the aid of machines, and thereby the importance of NC machines. NC technology is especially appropriate for low batch production; expensive and geometrically complex workpieces where high percentage of the material needs to be removed, as in the case of the aerospace industry. NC also provides the reduction of non-cutting time. As drawbacks, the NC technology requires a higher investment cost compared to manually controlled machines. Therefore, the equipment utilization need to be maximized to obtain economic benefits [21].

### 2.3 CIM and PLM

Computer Integrated Manufacturing, CIM, is “a process of integration of CAD, CAM and business aspects of a factory such as manufacturing, logistic operations, sales, marketing and finances” [15]. Thereby helping the management and control of the factory environment by linking the systems more efficiently.

Product Lifecycle Management, PLM, is “a systematic, controlled method for managing and developing industrially manufactured products and related information” [8]. PLM helps in the creation, recolection and storage of data related to products and activities, from the definition of a concept until the final disposal of the product. A PLM system integrates the functions of the whole company, thereby PLM can be the operational frame of CIM [22].

In order to ensure the re-utilization of information and knowledge in future projects, recolection and accumulation of data is needed along the product life. By doing this, endless possibilities are created such as the reduction of possible errors, the reduction of the preparation time or a more efficient utilization of
the machines. For instance, the knowledge recycling in the CAM system can be the creation of models that can be integrated into the CAM system and can easily access previous knowledge for use in future projects.

2.4 CAM

Computer Aided Manufacturing, CAM, is the effective use of computer technology in planning, manufacturing and controlling the manufacturing operation directly or indirectly [15, 21].

The inputs to the CAM process are the CAD models. The CAM software combines information of the workpiece and the tool geometry from the CAD models. As output, the CAM process generates the path that the tip of the tool will follow while machining the raw material in order to obtain the final part.

Previous research presented a CAM programming work flow, shown in Figure 2, that includes the steps from the design of the component to the machining of the parts [23]. This flow includes the steps from the model design, CAD, as the start point. Further, the flow also includes the steps corresponding to the process planning, CAPP, with the selection of the machining processes, the machines and clamping systems. Finally, the work flow includes the manufacturing steps, CAM, with the definition of the operations, the selection of tools, the selection of cutting data, the tool path generation, the post-processing of the generic cutting data and finally the machining of the part.

The development of a CAM program takes long time and several iterations and re-runs are normally needed along the process, including real tests at the machine, until the optimal cutting data is achieved. The use of a CAM system brings several possibilities such as work with both simple and advanced geometries, including free-form surfaces; simulate and verify off line the tool path generated without the need to dedicate machine time; or reducing the amount of prototypes needed during the development of new products [24].

Over the last decades, the industry has increased the degrees of freedom in the machines, increasing the flexibility in modern machine tools, and at the same time, decreasing the machine tool rigidity. This means that there is a higher risk of damages such as vibrations or tool wear during the production which need to be taken into account.
2.5 Fundamentals of Lean

The concept of Lean started in Japan after the World War II within the automotive industry [25]. Lean is a way of working, a philosophy, a culture in which the whole company needs to take part. According to the Japanese culture, the core of the production system is to eliminate waste or inefficiencies. The Lean principles [26, 27], are rooted in manufacturing but can yet be applied to other areas [28, 29]. The application of Lean generates both benefits and challenges. The benefits are cycle time reduction, work in progress reduction, cost reduction, productivity improvement, shorter delivery time, space saving, less equipment and human effort needed. The challenges are the statistical or system analysis not being evaluated, process incapability and instability, and people issues [30, 31].

Thus, the Lean philosophy tries to obtain the right product with the right quality at the right place and in the right time. The objectives of Lean are to reduce waste by reducing the activities that are non-value adding, thus reducing at the same time the cycle time [32].

In addition, an early and right decision is always less costly. A company needs to reduce costs, innovate and improve quality. Thus limiting what can be done to
continue being profitable. However, every company must know where the competitors are and have a clear picture of how they will develop and grow as a company [33].

In terms of organization, every company can be classified in terms of resource efficiency and flow efficiency, as presented in Figure 3 by the efficiency matrix [34]. The efficiency matrix is divided into four sections. The “Wasteland” section is where both resources and flow are poorly utilized. For instance, a company located in “Wasteland” is one that has no routines, standards or structures and needs to react to unexpected problems continuously. In order to improve, every company seeks to reach the “Perfect state”, which is when the company achieve both high resource efficiency and high flow efficiency. To achieve this, and as shown in Figure 3, there are two main paths that can be followed.

![Figure 3: Lean efficiency matrix, extracted from [34].](image)

One path starts by improving the efficiency of the resources (P 1) creating “Efficient islands”, in which the main focus is to maximize the resource utilization. In addition, this can create unwanted waiting time along the process. The other path starts by improving the efficiency of the flow (P 2) creating an “Efficient ocean”, which main focus is on the customers and their needs. With the customer as main focus, some of the resources will have free capacity. Further, along with all the improvements in both paths; secondary needs will raise. To be able to address those needs, the free capacity in the resources that exist in the “Efficient ocean” path, (P 2), will make this path the preferred one to reach the “Perfect state”.
2.6 From Lean to Sustainable manufacturing

Lean Manufacturing is based in the reduction of the resources used, such as materials, water or energy; and the reduction of the waste generated during the manufacturing of a product or component.

Further, Green Manufacturing was developed to reduce the environmental impact of the manufacturing industry [35]. In addition, the resource consumption was taken into account in terms of recycling and reutilization of materials and products.

Last, Sustainable Manufacturing aims to combine the efforts concerning the reduction of resources used and waste produced; the reuse of materials and products; the recycling of materials; the recovery of materials; and the redesign and remanufacture of new components or products [36].

2.7 Optimization fundamentals

An optimization problem searches for its optimal solution, which is the vector of decision variable values \( x \) within a certain set \( S \) that will provide the minimum value of the objective function \( f(x) \) among all the feasible solutions [37]:

\[
\min f(x), \quad \text{subject to } x \in S
\]  

(1)

In the case where several objectives functions need to be taken into account, a multi-objective optimization problem can be considered, which final solution needs to be selected from among the Pareto optimal solutions. Different methods can be used to find the preferred one, depending on the involvement of the decision maker, DM. A priori methods expect an input from the decision maker before the optimization. A posteriori methods produce a set of Pareto optimal solutions and the decision maker selects the most preferred one. Lastly, interactive multi-objective optimization methods involve the decision maker in the process and allow him/her to guide the solution process towards the most preferred one [38].

The Pareto optimal solution will be a vector of decision variables values where none of the criteria can be improved without impairing at least one of the other
criteria. It is possible to formulate a multi-objective optimization problem as follows [38]:

\[ \min \{ f_1(x), \ldots, f_k(x) \}, \quad \text{subject to } x \in S \]  \hspace{1cm} (2)

where \( f_i \) for \( i = 1, \ldots, k \) are the objective functions and \( S \) represents the non-empty feasible region, which is a subset of the decision variable \( \mathbb{R}^n \).

A decision (variable) vector \( x = (x_1, x_2, \ldots, x_n)^T \) belong to the (nonempty) feasible region (set) \( S \), which is a subset of the decision variable space \( \mathbb{R}^n \). Furthermore, a decision vector \( x^* \in S \) is Pareto optimal if there does not exist another decision vector \( x \in S \) such that \( f_i(x) \leq f_i(x^*) \) for all \( i = 1, \ldots, k \) and \( f_j(x) \leq f_j(x^*) \) for at least one index \( j \).
3 Superimposing a tool life equation and MRR

Material Removal Rate, \( MRR \), can be used as a metric to help every company to analyse and determine productivity of the cutting operations. Thereby, the efficiency in which the company is run can be evaluated. The selection of cutting speed, feed and depth of cut will determine the \( MRR \) value in which a cutting tool is used. Furthermore, the amount of time that a cutting tool can be used, namely tool life, is dependent on the same variables. Therefore, the combination of variables that will provide the same \( MRR \), will result in a different tool life, as represented in Figure 4.

![3D graph of a tool life equation superimposed on a constant MRR curve](image)

**Figure 4**: 3D graph of a tool life equation superimposed on a constant MRR curve.

3.1 Iso-MRR curves

With the objective to reduce the production time, or to remove the unwanted material rapidly, it is important for every manufacturer to have a metric such as the Material Removal Rate. \( MRR \) is the volume of material that is removed per time unit and given as a function of the cutting speed, \( v_c \), the feed, \( f \) and the
depth of cut, \( a_p \). For instance, in the case of longitudinal turning operation, the MRR is obtained as the product of the three mentioned variables:

\[
MRR = v_c f a_p
\]  

(3)

In this work \( a_p \) is considered to be constant, therefore MRR in (3) is a function of cutting speed and feed. Thereby, the constant material removal can be seen as iso-curves. The iso-MRR curve is obtained in a \( \{v_c, f\} \) graph by finding the cutting data combinations \( \{v_c, f\} \) that satisfy the condition

\[
\arg_{v_c,f} MRR(v_c, f) = Q_i
\]  

(4)

where \( Q_i \) is a specified MRR-level.

Figure 5 shows a family of iso-MRR curves for a fixed value of \( a_p \) and different values of \( Q_i \). Each iso-MRR curve, \( Q_i \), represents a doubling of the value of the previous curve, \( Q_{i-1} \).

Occasionally the feed rate is limited by the maximum mechanical load that the tool and the machining system can sustain creating a mechanical barrier. Similarly, the cutting speed is limited by the maximum thermal loads that the cutting tool can sustain, thus creating a thermal barrier. The barriers represented in Figure 5 are arbitrary depending on the cutting conditions at hand.

![Figure 5: Initial cutting data work frame for a certain tool defined by a mechanical barrier for the maximal feed and a thermal barrier for the maximal cutting speed. Family of iso-MRR curves considering constant depth of cut \( a_p = 2 \) [mm], including specified MRR-level as \( Q_i = 640 \) [cm³/min] on the bold curve. Each iso-MRR curve represents a doubling of the value of the previous one.](image-url)
3.2 Influencing variables

The three main variables that influence the cutting process are the cutting speed, the feed and the depth of cut, which constitutes the cutting data. In addition, there are several other important variables such as the material to be machined; the application of cutting fluid and its pressure considered as coolant conditions; and the cutting tool including the tool geometry, the tool material, and its coating [39].

Table 1 presents the summary of how an increase in one of the three main variables might influence in a positive or negative way in the value of Material Removal Rate, spiral cutting length, machining time, cutting area, tool wear, tool life, cutting forces, cutting power, temperatures generated and surface roughness achieved. (↑) represents a positive influence, (↓) represents a negative influence and (−) represents no influence [1, 3, 4, 40-47].

<table>
<thead>
<tr>
<th>Table 1: Main influencing variables during cutting process.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cut data:</strong> Material Removal Rate</td>
</tr>
<tr>
<td>Cutting Speed</td>
</tr>
<tr>
<td>Feed</td>
</tr>
<tr>
<td>Depth of Cut</td>
</tr>
</tbody>
</table>

3.3 The cutting process

The cutting process represents the art of removing unwanted material in form of chips; thus, transforming a shapeless block of raw material into the desired final geometry of the workpiece. Different cutting operations define how the material is removed. There are three main cutting operations or processes: turning, milling and drilling.
The cutting process is best described as two dimensional. Therefore, a short description of the orthogonal cutting process, is represented in Figure 6, where the cutting tool is depicted in yellow.

![Figure 6: Orthogonal cutting process in detail, extracted from [1].](image)

The cutting tool moves along the material at a cutting speed, \( v_c \), with a depth of cut, \( a_p \) and feed, \( f \). The contact between the cutting tool and the material creates a primary shear zone where the material is deformed and removed from the block in the form of chips. This contact defines as well the shear angle as the angle in which the material deforms and shears into the chip, or as the angle between the primary shear zone of the material and the workpiece.

As depicted in Figure 6, the clearance face of the cutting tool is the one in contact with the work material during the cutting operation. The clearance angle is the angle between the clearance face of the cutting tool and the work material. Similarly, the rake face of the cutting tool is the one in contact with the chip of material removed. Therefore the rake angle is the angle between the rake face and the perpendicular line to the work material.

### 3.4 The longitudinal turning operation

The longitudinal turning is a commonly used operation, shown in Figure 7, which was selected for the case study presented in Paper B, and for the analysis and selection of cutting data algorithm presented in Paper C. The process is presented here including relevant definitions used in this work \([1, 3, 48]\).
For this operation the depth of cut is defined as the difference between the workpiece diameter before, $D_0$, and after, $D_1$, the machining operation, divided by two:

$$a_p = \frac{D_0 - D_1}{2} \tag{5}$$

The contact area, $A_c$, between the cutting tool and the material during the cutting can approximately be defined as the product of the depth of cut and the feed:

$$A_c = a_p f \tag{6}$$

The cutting speed can be defined as the product of $\pi$, the initial diameter, $D_0$, and the spindle speed, $n$:

$$v_c = \pi D_0 n \tag{7}$$

The cutting power required, $P_c$, can be defined as the product of the specific cutting force, $k_c$, the feed, the depth of cut and the cutting speed:

$$P_c = \frac{k_c f a_p v_c}{60 \times 10^3} \tag{8}$$

The calculation of the spiral cutting length, $SCL$, can be simplified as the product of the perimeter, $p$, of the path that the tool describes and the length of the movement along the piece, $\Delta Z$, divided by the feed.
SUPERIMPOSING A TOOL LIFE EQUATION AND MRR

\[ SCL = p \frac{\Delta Z}{f} = D_o \pi \frac{\Delta Z}{f} \]  

(9)

The machining time, \( t_m \), can be defined as the fraction between the length of the material, \( L_z \), and the feed speed, \( v_f \), which equivalently can be defined as the product of feed and spindle speed:

\[ t_m = \frac{L_z}{v_f} = \frac{L_z}{f \pi} \]  

(10)

In addition, the effective machining time can be calculated as the spiral cutting length divided by cutting speed:

\[ t_m = \frac{SCL}{v_c} \]  

(11)

The total volume of material removed, \( V \), can be calculated as the product of the feed, the depth of cut, the cutting speed and the machining time:

\[ V = f a_p v_c t_m \]  

(12)

The average surface roughness, \( R_a \), can be calculated as a function of the nose radius of the cutting tool, \( r_e \), and the feed, \( f \):

\[ R_a = \frac{f}{32r_e} \]  

(13)

3.5 The hole making process

Hole making can be divided into several operations, as represented in Figure 8. A spot drilling operation is used first to center the hole. Subsequently, the drilling operation, considered as rough or semi-finishing operation, helps to remove the majority of the material. The cutting data used during the drilling process will provide the geometry, accuracy, hole roundness and center required. Lastly, the reaming operation, which is meant to provide the final geometry, accuracy and surface finishing in the machined hole of the workpiece is considered a finishing operation. In addition, burr is sometimes present at the bottom surface of the hole, thus deburring operations might be needed for its removal [1].
A short introduction to the formulas that govern the drilling operation is presented. These will be used for the study and optimization of the operation.

The cutting speed can be obtained as the product of the machined diameter, $D_c$, which in this case will be the same as the drill diameter, the constant $\pi$, and the spindle speed [4, 48, 49]:

$$v_c = \frac{d \pi n}{10^3}, \quad d \in [0, D_c]$$  \hspace{1cm} (14)

Furthermore, the cutting speed will vary along the drill radius. This value has its maximum in the drill periphery and reduces its value until it becomes zero in its center, as illustrated in Figure 9.

The feed per revolution is “the distance that the drill travels into the workpiece per revolution” [1]. The feed speed can be obtained by the product of the feed per revolution and the spindle speed [4, 48, 49]:

$$v_f = f n$$  \hspace{1cm} (15)

Each drill or drill bit has a number of flutes or teeth, $n_t$. Therefore the feed per tooth, $f_t$, can be obtained by [4]:

$$f_t = \frac{f}{n_t}$$  \hspace{1cm} (16)

The effective depth of cut per flute, $a_p$, is half of the drill bit or machined diameter [4]:

$$a_p = \frac{D_c}{2}$$  \hspace{1cm} (17)
Figure 9: Representation of drilling process by using a drill bit with two teeth.

The effective machining time to drill a hole of depth $L$, can be calculated, as an approximation, as the length of the hole divided by the feed speed [4, 49, 50]:

$$t_m \approx \frac{L}{v_f}$$  \hspace{1cm} (18)

The time required for drilling of $N_h$ number of holes by using $N_t$ number of cutting tools is comprised of two parts, namely the cutting time and the non-cutting time. The non-cutting times in a drilling operation are the start and stop times per tool, $t_{s-s}$, the engagement time for each hole, $t_{eng}$, the time to retract the tool for each hole, $t_{retr}$, the time to move from one hole to the next one, $t_{mov}$, and the tool change time per tool, $t_{tch}$. The total operation time can be calculated as the sum of all the above times and the machining time for each hole, $t_m$, as:

$$t_{tot} = t_{s-s} + (t_{eng} + t_m + t_{retr})N_h + t_{mov}(N_h - N_t) + t_{tch}N_t$$  \hspace{1cm} (19)

The time required for start and stop, as well as tool change, which depends on the machine used, can be measured and considered constant. The engagement, machining and retraction times depends on the geometry of the cutting tool and the workpiece. The time required for the movements from one hole to the next depends on the geometry of the workpiece and the machine. Lastly, the tool change time depends on the machine used. It may be noted that the tool change point in drilling whenever it is needed is when the drill bit has drilled a complete hole, either blind or through, and the tool is retracted. By only drilling complete holes, it is ensured that the surface finish obtained is consistent.
The material removal rate can be calculated as the product of the transversal area of the hole and the feed speed. When applying Equation (15) and Equation (14), the material removal rate can be expressed as the multiplication of the machined diameter or tool diameter the cutting speed and the feed per revolution, all divided by four [4, 48, 49, 51]:

$$MRR = \frac{\pi}{10^3} \left(\frac{D_c}{2}\right)^2 v_f = \frac{\pi D_c^2}{4 \times 10^3} n f =$$

$$= \frac{\pi D_c^2 \times 10^3 v_c}{4 \times 10^3 \pi D_c} f = \frac{D_c v_c f}{4}$$

(20)

The power required during the cutting operation, $P_c$, can be calculated as a function of the material removal rate and the specific cutting force, $k_c$. When applying Equation (20), the cutting power can thereby be calculated as a function of the feed per revolution, the cutting speed, the drill diameter and the specific cutting force of the material [48]:

$$P_c = \frac{MRR \ k_c}{60 \ 10^3} = \frac{f v_c D_c k_c}{240 \ 10^3}$$

(21)

Each of the cutting edges of the drill bit will follow a path which length can be calculated as the spiral cutting length. As an approximation, SCL can be calculated as the multiplication of the drill or machined diameter, the hole length and $\pi$, all divided by the feed per tooth. This represents the perimeter of the hole multiplied by the number of revolutions that the tool takes to travel the whole machined length:

$$SCL = \frac{\pi D_c L}{f_t}$$

(22)

Drilling, in most cases, is not considered a finishing operation, as is the case of reaming. However, the surface finish created during one cutting operation will influence the next one. If the surface roughness is large, the cutting area will vary during the following operation. This can create variations in the cutting forces and required cutting power along the machining operation.

The maximal surface roughness, $R_{max}$, can be calculated by the feed per tooth, $f_t$, divided by four times the tangent of the secondary cutting edge angle, $K_f'$ [4]:

$$R_{max} = \frac{f_t}{4 \ tan \ K_f'} = \frac{f}{4 n_t \ tan \ K_f'}$$

(23)
3.6 Workpiece material

The workpiece material is normally selected depending on the application of the component produced. As this work is oriented towards the aerospace engine industry, there is a need for materials that will keep their strength under the tough working conditions of such components. Heat resistant super alloys, HRSA, are used in those conditions due to their retention of strength and hardness at high temperatures and their corrosion resistance [52]. Nickel-based alloys are widely used in such applications. The characteristics of this material are lower thermal conductivity, work hardening, presence of abrasive carbide particles, hardness, chemical affinity, i.e. its propensity to react with the tool material among others. Therefore, the material is classified as difficult-to-machine [53].

3.7 Cutting tool materials

Cutting tools have been developed for centuries, driven by the search for an improved toughness and hardness. This has allowed a substantial increase in manufacturing productivity. The cutting tool materials were mainly developed during the 20th century and range from steels to cemented carbides, ceramics, diamonds and boron nitride. Their selection depends on the workpiece material.

The desired properties of cutting tool materials are hardness, wear resistance, toughness, deformation resistance, hot hardness, heat resistance, chemical resistance, tendency not to stick to the workpiece material, producibility and cost [3].

Since this work is oriented towards the aerospace engine industry, the workpiece materials considered are HRSA. Therefore, the cutting tool materials recommended are High Speed Steel, Cemented Carbides and Ceramics [54]. The use of High Speed Steel has decreased in favour of both Cemented Carbides and Ceramics. These cutting tool materials possess the desired properties necessary to machine HRSA needed to reduce too rapid tool wear. Furthermore, the selection of the cutting tool material by the CAM Programmer, together with the cutting data leads ultimately to a successful and robust cutting operation [54].
3.8 Tool wear

Several parameters determine how the cutting tool will wear and deteriorate; the type of wear; and at which rate the tool wear occurs. Influential parameters of the tool wear are the cutting tool geometry, material and coating; the cutting conditions including the cutting data, the type of cutting operation and the application of cutting fluids; as well as the workpiece material [54, 55].

These parameters will affect the contact stresses between the workpiece and the cutting tool, and thus the prevailing temperature in the cutting zone. Therefore the tool wear is dependent on factors such as loads, temperatures and chemical reactions. Every basic physical mechanism, in a specific cutting operation, will expose a certain wear type. For instance, abrasive wear mechanism will result in flank wear; diffusion wear mechanism, as thermo-chemical process, will result in crater wear; adhesion wear mechanism will result in built-up-edge (BUE); and fatigue, due to cyclic loads of temperatures, forces and/or stresses, will result in plastic deformation or cracks [54].

The tool wear can emerge either as premature or gradual failure of the cutting tool. High cutting forces can develop a premature brittle failure. In order to reduce or mitigate this, new cutting tool geometries, materials and coatings are continuously researched. Similarly, elevated temperatures generated by the cutting process can develop premature failure due to effects from thermal overheating. Cutting fluids are commonly used for its reduction or mitigation, attempting to extend the tool life of the cutting tools [56]. A premature failure will lead the cutting tools to a catastrophic event occurring over a very short period of time, which is unpredictable, while a gradual failure of the cutting tools can be predicted. Moreover, the cutting tool can be used for a longer period of time and, therefore this is the preferred failure mode of the tools.

In the case of gradual failure, tool wear has a rapid initial wear as a break-in period. Thereafter, a period that exhibits uniform wear rate at a steady-state and finally an accelerating wear rate until its catastrophic or final failure, as shown in Figure 10 [57].
3.8.1 Flank wear

Flank wear occurs on the clearance face of the cutting tool, which is the one in contact with the workpiece material during the cutting operation. Flank wear, as illustrated in Figure 11, is predominant at low cutting speeds and abrasive wear is the dominant mechanism. This type of wear is easily measurable, therefore it is normally used as the wear criteria limit \( (V_B) \) \([54, 58]\).
3.8.2 Crater wear

Crater wear occurs on the rake face of the cutting tool, which is the one in contact with the chip during the cutting operation. Crater wear, as represented in Figure 12, is predominant at high cutting speeds. Diffusion wear is the dominant mechanism as consequence of the chemical reaction between the cutting tool and the workpiece materials due to elevated temperatures. Crater wear can weaken the cutting edge to the point of fracture [54].

![Figure 12: (a) Cutting tool illustration with indication of the view of the left image. (b) Crater and Nose radius wear schematic of the rake face, extracted from [1].](image)

3.8.3 Wear in a drill bit

In the case of drill bits, it is possible to detect and measure the flank wear on the clearance face of each of the teeth or flutes of the drill bit. Similarly, the crater wear occurs on the rake face of the teeth or flutes as a result of the contact between the drill bit and the chip. In addition, wear will occur on the chisel edge of the drill bit, as represented in Figure 13.

![Figure 13: Illustration of the flank wear, crater wear and chisel edge wear in a drill bit with two teeth [4].](image)
3.9 Tool life

Tool life can be described as the amount of time that a cutting tool can be used until the flank wear has reached the tool life criteria [40], as shown in Figure 14. The diagram shows the influence of the cutting speed on the cutting tool life, \( T \), where a lower value of cutting speed will wear the cutting tool in a lower rate increasing the amount of time that can be used until the tool life criteria is reached, thus increasing the tool life.

![Figure 14: Relationship between the flank wear criteria \( (V_p) \) and the tool life \( T \) for different cutting speed values and a selected tool wear criteria limit \( (V_{bn}) \).](image)

The effective cutting time is directly related to the cutting length. Similarly, and following Equation (11), in the case of longitudinal turning operation, tool life can be described as the length, \( SCL \), that a tool can be used until the flank wear has reached the tool life criteria, which is commonly used [59, 60] and could be represented similarly to Figure 14.

As an example of tool life, the common tool wear criteria for the high speed steel and ceramic tools are catastrophic failure; 0.3 mm of flank wear if the flank is regularly worn; or 0.6 mm if the flank is irregularly worn, scratched or chipped [57, 61]. In addition, the wear criteria for cemented carbide tools commonly use similar values.

In this work, it was considered that during a cutting operation, the tool will not present an early failure, neither brittle nor thermal, due to high cutting forces or high temperatures. Instead, the used tool wears and deteriorates gradually until the flank wear reaches its selected tool wear criteria limit, \( V_{bn} \).
3.10 Taylor tool life equation

Over the last century, several researchers have developed models to describe the cutting tools’ wear progress over time. Some of the most commonly used tool wear rate models are: Taylor’s tool life equation [40]; Takeyama and Murata’s wear model [62]; Usui’s wear model [63]; Archard’s wear model [64] and Colding’s tool life equation [4].

Several of the tool life equations take into account cutting temperatures, loads and/or stresses which are difficult to measure during a cutting operation, hence the difficulty to obtain the experimental constants.

Other CAM simulation studies [65] consider the cutting data (cutting speed, feed and depth of cut), together with part geometry, spindle speed and type of tool as the most influencing variables in the machining process. Therefore, Taylor’s tool life equation has been selected as tool wear model for this work:

\[ v_c T^\alpha = C \]  

(24)

Where \( T \) is the tool life, \( v_c \) is the cutting speed, as before, while, \( \alpha \) and \( C \) are empirically determined constants. \( \alpha \) is related to the negative slope of the tool life curve when represented in a log-log scale, as shown in Figure 15. \( C \) represents the cutting speed for which the tool life is one minute [40].

![Figure 15: Taylor tool life curve representation on a log-log scale.](image)

The original Taylor’s tool life equation (24) takes into account just the influence of the cutting speed on the tool life. With the development of carbides and other tool materials, the influence of feed and depth of cut became significant as well. Thus the development of the extended Taylor’s tool life equation is:
\[ v_c T^\alpha f^\beta a_p^\gamma = C_t \]  

(25)

Where, \( \alpha, \beta, \gamma \) and \( C_t \) are constants empirically determined for each specific combination of cutting operation-work material-cutting tool used [43]. These are related to the contribution from each parameter to the tool wear. A large value indicates a strong influence to the tool wear, thus decreasing tool life as a consequence.

The four constants \( \alpha, \beta, \gamma \) and \( C_t \) can be obtained from different empirical catalogue data points provided by the tool supplier. As shown previously [66], it is possible to construct a system of four equations with four different “working points or data” collected and convert these equations from non-linear to linear; obtaining a system of four linear equations, see Appendix A. Thereby, allowing the calculation of the constants by using four different data points.

For this work, four cutting data points were selected from [67] for a rough turning operation on a component made from HRSA with a ceramic cutting tool. These are presented in Table 2.

<table>
<thead>
<tr>
<th>( v_c )</th>
<th>( f )</th>
<th>( a_p )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.6</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>40</td>
<td>0.4</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>200</td>
<td>0.24</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Solving the linear system of equations gives the values for the Taylor tool life equation constants, presented in Table 3.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( C_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>240</td>
</tr>
</tbody>
</table>

From the results obtained, the influence of the feed will be similar to the influence of the cutting speed and the depth of cut has little or negligible impact the tool life.

The expected values from literature [42, 43, 50] are that \( \alpha \) is within the range of 0.5 to 0.7; \( \beta \) should be smaller than 1 because the influence of feed is less significant than the influence of the cutting speed; and \( \gamma \) should be smaller than
because the influence of depth of cut is less significant than the influence of
the feed. Therefore, by comparison with the results obtained, it is possible to
appreciate the conservative values given by the tool suppliers.

3.11 Expected Tool Life (ETL), Utilized Tool Life (UTL) and Remaining Tool Life (RTL)

A cutting tool can be used for a sequence of machining operations using
different machining parameters \( \{v_c, f, a_p\} \). Thus, the extended Taylor’s tool life
equation will become a time varying function of the time varying cutting data, as
represented in Figure 16.

![Figure 16: Illustration of a piece-wise constant Taylor’s tool life for three subsequent machining operations with different cutting data.](image)

A cutting tool supplier often provides a set of recommended cutting data. This
data, however, may not be the most suitable for a specific machining operation.
It depends on many factors, such as the intended tool path including its
complexity and length. To find the most beneficial operating point for the
cutting tool, three variables must also be taken into account. These are the
Expected Tool Life, \( ETL \), Utilized Tool Life, \( UTL \), and Remaining Tool Life, \( RTL \).

In this work, the extended Taylor’s tool life equation (25) is used to estimate the
expected tool life by
The general expression for utilized tool life is given as the ratio between the effective machining time $t_m$ and total $ETL$. In the general case when multiple subsequent operations are performed with the same cutting tool, the cutting speed, feed, and depth of cut may be altered. The tool utilization is given with the effective machining time and $N$ machining operations as:

$$ UTL\% = \frac{t_m}{ETL} \times 100\% = \sum_{k=1}^{N} \frac{t_k}{ETL(v_{c,k}, f_k, a_{p,k})} \times 100\% $$

where $t_k$ denotes the machining time for the $k$:th operation. The total machining time is given by:

$$ t_m = \sum_{k=1}^{N} t_k $$

The remaining tool life is obtained by subtracting the total machining time from the expected tool life:

$$ RTL(v_c, f, a_p) = ETL(v_c, f, a_p) - t_m $$

Remaining tool life can also be obtained by subtracting $UTL\%$ from the total as:

$$ RTL\% = 100\% - UTL\% $$

This implies, that in order to optimize tool utilization and to be able to obtain a reliable estimation of the $RTL$, the complete history of operations and cutting data used (including the machining time and/or the cutting length) for a specific cutting tool, must be registered and documented. Therefore, any optimization routine must monitor, or at least keep a record of, the life of each cutting tool.

### 3.12 Machining cost for drilling operations

The total cost per workpiece can be calculated as the sum of the material cost, the labour cost, the machine cost, the tool cost and other costs such as those associated with inspection and/or overhead costs [68]. The machining cost, $C_m$, is the sum of labour, machine and tool costs as signified in Equation (31). The labour cost can be calculated as the product of the total operation time, $t_{tot}$, and
the labour wage, $C_{lab}$. Similarly, the machine cost can be calculated as the product of the total operation time, $t_{tot}$, and the machine cost, $C_{mac}$. Lastly, the tool cost can be calculated as the product of the machining time of one hole, $t_m$, the number of holes to drill, $N_h$, and the tool cost, $C_{tool}$, including both the cutting tools and the tool holders costs, divided by the ETL of the drill bit measured in number of holes [69].

$$C_m = C_{lab}t_{tot} + C_{mac}t_{tot} + C_{tool} \frac{t_mN_h}{ETL} \tag{31}$$
4 Sustainable manufacturing

Sustainability is defined by Brundtland as: “…development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [70, 71]. Economy, environment and society are the three main pillars of sustainability [72]. In 1994, the triple bottom line or three Ps were defined. The Profit (Prosperity) or economy pillar represents financial health of the enterprise, including resource utilization. The Planet or environment pillar seeks the no harm and restoration of the environment. Last, the People or society pillar defines how the company treats the employees [73].

The main objective for the manufacture of a component has been productivity, followed by manufacturing cost. However, manufacturing has consequences in environmental and societal terms, not only economical. Over the last decades, different researchers have stressed the importance of the balance between all three sustainability pillars [74]. Thus, manufacturing companies are also beginning to be evaluated in terms of environmental, economical and societal aspects.

4.1 Sustainable manufacturing processes

Sustainable manufacturing is defined by the U.S. Department of Commerce as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers, and are economically sound” [75]. Thus, sustainable manufacturing “must demonstrate reduced negative environmental impact, offer improved energy and resource efficiency, generate minimum quantity of wastes, and provide greater operational safety and personal health, while maintaining and/or improving the product and process quality” [76]. Furthermore, the main objectives of sustainability are: reduction of manufacturing cost; reduction of product development time; reduction of material use; reduction of energy consumption; increased operational safety; enhanced societal benefits; reduction of industrial waste; repair, reuse, recovery and recycling of used products/materials; consideration of environmental concerns; education and training of workforce; and increased product and process innovation [72]. Thus sustainable manufacturing will provide: improved environmental friendliness; reduced cost; reduced power consumption; reduced
wastes and more effective waste management; enhanced operational safety; and improved personnel health [77]. In addition, sustainable manufacturing processes can be defined as “those which generate minimum quantity of wastes demonstrating improved environment impact and energy efficiency while providing operational safety and personnel health” [78].

4.1.1 Basic elements of a sustainable manufacturing process

According to Wanigarathne et.al., the sustainable manufacturing process has six basic elements: environmental impact, energy consumption, waste management, manufacturing cost, operator safety and personnel health [79]. Similarly, De Silva et.al., identified the six major sustainability elements: environmental impact, functionality, manufacturability, recyclability and remanufacturability, resource utilization/economy and societal impact [80]. Lu et.al., identified the six major sustainable elements: environmental impact, energy consumption, waste management, manufacturing cost, personnel health and operator safety [81].

4.2 Manufacture of a component

The manufacture of a component starts with the extraction of the different materials needed, represented in Figure 17. Furthermore, a first material processing to allow manufacture. From a manufacturer’s perspective, these two steps, together with the design of the component or product integrate into the pre-manufacturing, PM, stage [72]. The manufacturing, M, stage will require several processes such as machining, welding, forming and assembly. These processes transform the initial block of materials into the final product. Machining, in particular, is one of the most important manufacturing process, and is estimated to contribute about 5% of the GDP in the developed world [36]. The use, U, stage is related to the life time of the product while is used by the customer, including upgrades, repairs and maintenance to prolong its life time. Lastly, the post-use, PU, stage is the final processing of a product for its end-of-life, including disposal or disassemble and sorting of the different materials and components to potentially reduce, recover, reuse, remanufacture, recycle, and/or redesign [72, 82].
4.2.1 6R’s: Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture

There are six end-of-life activities or processes identified within the post-use, PU, stage of a product, that differ from disposal to landfill:

Reduce focus on all stages of the product life-cycle, including the reduction of resources, materials and energy used, and the reduction of the waste generated [36].

Reuse of products or components instead of the production of new ones can reduce, for instance, the material, energy and water used for its extraction [36].

Recycle materials in products or components that otherwise are considered as waste can further reduce the use of new materials [36].

Recover products involve the recollection and sorting processes for further shredding and recovery of the materials [83].

Redesign of products or components involve the use of knowledge and information to streamline the design of a new generation product. For instance, by the application of the Design for Environment [36]. Redesign can clearly influence the society pillar, as in the example proposed by Ungureanu et.al., where the vehicle will absorb the crash forces, therefore will be safer for the passengers [84].

Remanufacture of products or components involve the manufacture for similar or different applications, such as upgrading or repairing.
4.3 Sustainable evaluation

During the manufacture of a workpiece, several contributions need to be taken into account: the raw material, the cutting tools, the machine tool utilized and the selected machining processes. This is schematically depicted in Figure 18. Once the materials involved and total material volume for each process have been established, the cost, the amount of energy and other resources required to produce the workpiece as well as resulting emissions can be estimated using standard data [85].

Previous studies have dealt with different regulations that exist in Japan, United States or other countries within Europe as well as the importance of the environmental footprint and how can it be measured [86], which is elaborated upon in this work.

![Figure 18: General illustration of contributions in the estimation of energy use, cost, CO₂-footprint and water usage of a theoretical workpiece.](image)

4.3.1 Energy consumption

The total energy use for both the workpiece and the cutting tools can be calculated as the sum of the embodied energy from the primary production of the materials and the energy used on the processing of those materials. For energy and CO₂ values, the included processes are rough rolling of the blank material, grinding of the cutting tool materials, rough and fine machining of the workpiece material.
The embodied energy of materials are presented as a range of values in the standard engineering software platform CES Selector [85]. These values are dependent on several different variables such as the material extraction place and the scale of production in that country.

Given the density of the material and the volumes of the blank and the workpiece, it is possible to calculate the mass. By using the ranges of values provided by the mentioned database, is it possible to estimate minimum and maximum values of the energy use during primary production and processing.

4.3.2 Cost considerations

Manufacturing costs can generally be considered as the sum of the material cost including consumables, tooling and equipment costs, the overhead costs including labour, administration and rent, the cost of energy and other costs such as research and development or royalty payments [87].

The material price given in the database is an approximate price for high volume purchase from a primary producer. Further processing of the material is applied either at the cutting tool supplier or the material supplier [85], as indicated in Figure 18. As a simplification, the equipment cost for machining the workpiece will dominate the processing costs. There is only a rough estimate of processing costs, using criteria presented in Paper F.

Cutting tool cost will vary depending on different characteristics such as the tool material, size, shape, chip-breaker features and coatings. Cutting tool cost usually represents a small percentage, 2-4 %, of the manufacturing costs [13]. However, that value can increase significantly when machining HRSA.

4.3.3 CO₂, NOₓ and SOₓ Emissions

One important part of the environmental footprint of a manufactured product can be measured as the amount of carbon dioxide, CO₂, produced and released to the atmosphere during the production of 1 kg of material. This is a greenhouse gas and originates mainly from fossil energy use. Although NOₓ and SOₓ emissions can also be directly related to the amount of energy required [88], only CO₂-footprint have been considered in this work.
4.3.4 Water usage

While seawater is extremely abundant, constituting 97% of the water on earth, accessible fresh water accounts for less than 1%. The water usage for materials corresponds to the amount of fresh water required to produce 1 kg of material. Approximate total values for the material of a product can be extracted from the inputs and outputs measurements of the factory [85]. Water usage in the processing represents the water consumed by the local material processing operation. This includes the water required to operate the processing equipment and all other requirements of the facility. However, this does not include recirculation of water used in cooling systems or non-polluted water returned to the same water catchment.

The water used by the processing is derived from:

- The water evaporated or polluted to cool the material during processing;
- The water required for annealing, pickling and rinsing, if these are involved in the process;
- The water lost by evaporation during the process or in cooling towers;
- The indirect water of electricity generation and supply.

The water associated with these operations is strongly dependent on on-site specific conditions such as: machine type, cooling technologies, wastewater treatment, etc.
II. INVESTIGATION CHAPTERS

5 Study of the CAM programming work flow from the Lean perspective

As a first approach to the CAM programming area within the aerospace industry, three CAM Programmers were interviewed. The aim with these interviews was to get an understanding of the current situation in terms of how the CAM Programmers structure and conduct the CAM programming process, how they are organized and how they relate to the different projects. Thereby, it is possible to investigate the inefficiencies within the CAM programming process and how the available resources are used.

The method used to collect the necessary data is semi-structured interviews with an open question. Thus, the interviewees could neither be influenced nor guided in their answers. Three CAM experts were asked to describe the steps that they follow when developing a CAM program and freely discuss the subject. Each of the CAM experts selected for the interviews have over 10 years of experience, working with different machining methods such as turning or drilling. Note that as a limitation, the study of the CAM programming process is centred in one company within the aerospace industry.

As an alternative to interviews, observation was considered, however rejected due to time consumption and the high risk for reflexivity (influence between interviewer and interviewees). Surveys were considered as well, however the questions required at this stage were too general for a survey.

When interviewing, there is always a risk that the interviewee adjusts the replies to the expected response. The interviewees involved could provide a clear view of the situation; provide explanations as well as personal views. Different views from the interviewees corroborated that the interviews were not biased in any “conspiratorial” way between the interviewees, or by reflexivity [89].
5.1 Description of the CAM programming work flow

A detailed work flow of the CAM programming process was constructed from the semi-structured interviews to CAM Experts. Mentioned work flow and its description are presented in Appendix B, Figures B.1 to B.3.

The CAM programming work flow starts with the interpretation of the drawing or model of the component, as step one. A total of twenty one steps lead to the inspection of the first approved component from production, thus defining the closing step of the CAM programming work flow.

In addition, the work flow can be divided in three main stages, represented in Figure 19. The first stage is the one corresponding to the process planning, including the secondary flows for tool selection and clamping system selection. The second stage, corresponds to the definition steps. Last, the third stage, corresponding to the programming for manufacturing.

Along the CAM programming work flow, the involvement of other stakeholders might be needed at different steps. For instance, during the process planning stage, a rough estimation of the process is done thanks to the experience of the
CAM Programmer and the involvement of different stakeholders such as the Material Expert, the Process Expert or the Production Planner.

In the case of both secondary flows, i.e. tool selection and clamping system selection, the Tool Supplier and the Fixture Designer will be the responsible for the corresponding step.

Furthermore, the involvement of other stakeholders during the operation definition and machining parameters selection steps might be crucial. For instance, there are of exceptional value the inputs and feedback that the Operator can provide from production. Thereby, these steps are performed thanks to the experience and know-how of not only the CAM Programmer, but also the Process Expert and the Production Operator.

Last, the real test and the component inspection steps require the additional involvement of Production Operator and the Inspector.

5.2 Analysis of the CAM Programming work flow

The CAM Programming work flow was guided by interviews of CAM Experts within one aerospace company. Therefore, even though similarities can be found with respect to the generic work flow presented in Figure 2, more details were needed for the Lean study. As a result, the generated work flow is specific for the studied company.

Every company looks to reduce the machining time, as is the case of the aerospace engine industry, thus the blank selection is done as “near net shape”. Thus the amount of material to be removed is kept to the minimum.

In the aerospace industry, manufacturing has normally independent stations and every part follows a different flow along them. One of the difficulties is to find the right combination of all the machines needed and their corresponding availabilities, thus the need of involvement of the Production Planner.

The delivery time of cutting tools and tool holders may take several weeks. The selection of a tool that cannot sustain the loads during the cutting, or cannot remove the amount of material in the stipulated time, can lead to the need of a new cutting tool including its definition and development. Which can be further translated into delays. Similarly, the time required to define, generate and fabricate the clamping system may also take several weeks. The clamping system
has an impact on the stability of the cutting process and therefore affects the final dimensions and tolerances of the component, which is particularly important during the machining of thin-walled components.

Furthermore, the initial cutting data selected will determine the number of iterations needed to reach the optimal cutting data. Thereby the importance of the good use of internal know-how of the company and the involvement of other stakeholders.

The CAM Programmers works with three different software. First, a definition software is used to define and keep all the different models required, which serves as link between software within the company and allows traceability. Second, a CAM software for programming, generating the tool path, simulation and verification. Last, as a specific requirement in the aerospace engine industry, a second software is needed to perform a simulation and verification of the generated and post processed code. Thereby simulating as close to reality as possible before a real production test is performed.

5.3 Study of the CAM programming work flow from the Lean perspective

In order to identify the key steps along the CAM programming work flow, an evaluation of each step has been performed with regard to three different criteria, presented in Paper A, Table 1. The first criterion is the relevance or importance of the step, mainly depending on the consequences that an erroneous decision at that step can generate in terms of time, and thereby cost. The second criterion is the time needed to perform the step, which can vary from minutes to weeks. Third and last criterion is the level of skills or experience required by the CAM Programmer to perform the step, which can be translated into the understanding of the different processes, materials, machine tools, cutting tools, etc. All criteria have been classified into three different levels as low, medium or high. In the case that at least two of the three criteria are evaluated as high, the step is considered as a key step.

There are eight key steps from the twenty-one that integrate the CAM programming flow, presented in Paper A, Table 1. The key steps can be arranged in two groups. The first group contains the process planning, which includes process selection, machine selection, cutting tool selection and clamping system
The selected processes provide the basis for productivity, which is considered high relevance.

The machines to be used will affect the way the company uses its machine tools park and is therefore considered high relevance. The tool selection and the clamping system selection are both time consuming. Both steps influence the machining operations and the dimensional accuracy of the component, which resulted in high importance and high skills required.

The second group contains all the key steps during the programming for machining, which include operation definition, machining parameters selection, tool path generation and simulation and verification. These steps require a large amount of time due to all the iterations needed to obtain the optimal cutting data that will assure both productivity and quality of the component. Therefore, for these four steps, the relevance, the time needed and the skills required of the CAM Programmer are all considered high.

5.4 Findings

The CAM programming work flow emulates a “production line” and helps to visualize how the different “operators” work along the flow. Each step can be seen as a “station” within a “production line”, which is initiated by the CAD model, executed by the CAM Programmer and finalized by the creation of the CNC program describing the tool path to machine a workpiece. Therefore, the CAM programming work flow is detailed enough to perform an analysis from the Lean perspective.

To perform the initial steps (1-5) considerable experience in different fields is required, which can be translated into the understanding of the different processes, materials, machine tools, cutting tools, clamping systems and relative or approximate costs. Therefore, other stakeholders need to be involved in the project. Furthermore, the presence of a CAM Programmer in earlier stages of the project will influence in the decisions about, e.g., production, dimensions or tolerances, and assure as low machining cost as possible.

Further development of software features to simplify the CAM Programmer’s work could simplify the key steps that require large amounts of time and experience. In addition, it is important to mention the need for every company to keep the gained knowledge within the company, to be reused in future projects, simplifying and reducing the programming time. However, the use of
both technological and organizational improvements in any company leads to an improved overall performance [90].

5.4.1 Current company specific organization

Looking into the organizational aspects, the CAM Programmers are commonly organized exclusively by machining methods. According to the efficiency matrix [34], the resources, in this case the CAM Programmers, are highly efficient. They each represent an “Efficient island”. However, there is a need to increase the flow efficiency. First an “Efficient ocean” needs to be created by freeing up capacity from the resources. Thereafter, the efficient use of the resources and the flow efficiency can be increased towards the “Perfect state”, as represented in Figure 20.

![Efficiency matrix](image)

Figure 20: Efficiency matrix extracted from [34]. Path from effective islands, through effective ocean to perfect state.

The current organization of the CAM Programmers could be represented by a “short and fat” layout [91], indicated Paper A, Figure 1. This layout has advantages such as flexibility, robustness and non-monotonous work. In a “long and thin” layout [91], where each step will be performed by a different CAM Programmer; it will take too much time for each CAM Programmer to interpret what has been done in previous step to be able to work with it, due to the complexity of the parts, which is a major drawback. Therefore a “mixed” layout could be a good solution in the path towards the “Perfect state”.
5.4.2 Lean CAM Programmer’s reorganization

The Lean organization of the CAM Programmers aims to allocate the more experienced people in the key areas and the less experienced people in non-key areas. Two organizational proposals are presented and depicted in Paper A, Figure 1.

First, an expert group can work during the planning process stage (steps 1-5 of the CAM Programming work flow), where more experience is required from the CAM Programmer. Furthermore, a dedicated person is proposed to work with the definition stage (steps 6-11 of the CAM Programming work flow), where less experience is required. Lastly, a CAM Programmer will continue the work flow until the program is frozen and ready for production (steps 12-21 of the CAM Programming work flow).

The first organizational proposal allocates the CAM Programmers, similarly to the current organization, based on the different machining methods such as turning, milling or drilling, see Figure 21.

![Figure 21: First organizational proposal as “mix” layout.](image)

Up to now, the CAM Programmers’ organization has been based with the main focus in the different machining methods. Influenced by the automotive industry, other industries are orienting their product development towards platforms. These platforms might allocate several products that will share characteristics such as sizes, materials, shapes or features. Therefore, the CAM Programmers can be allocated, for instance, based on features [92].

The second organizational proposal, as presented in Figure 22, aims to allocate the CAM Programmers within a feature-based organization. Each product can be divided by its different features and thereby the CAM Programmers could be divided similarly. Shafts, hubs, blades, shrouds or flanges are examples of features within the aerospace industry.
This organizational proposal has as main benefit the possibility to streamline the CAM programming process by improving the work flow efficiency. An extra benefit from the use of platforms is that it might guarantee that the knowledge gained during one project will be reused, at least, in other projects within the same platform. However, this organizational proposal will split the CAM Programmers and allocate the most experienced people in an expert group. This strategy can lead to the creation of a separation between the experienced and non-experienced CAM Programmers. Therefore, the continuous training of all CAM Programmers is recommended to minimize the possible segregation, assure a seamlessly communication between all the CAM Programmers and add even more flexibility to the organization.
6 Analysis of tool utilization

A recommended set of cutting data is often provided by the cutting tool supplier. For a rough operation, the used values will be the highest recommended by the tool supplier for a specific cutting operation - workpiece material - cutting tool combination. However, depending on factors such as the intended tool path including its complexity and length, the recommended cutting data might not be the most suitable.

To find the most beneficial operating point for the cutting tool, expected tool life, $ETL$, and utilized tool life, $UTL$, need to be taken into account. By having access to this information, potentially less remaining tool life (or moderately used tools) will be thrown away as waste, leading to an overall higher utilization of the cutting tools.

As a way to study how the cutting tools are used in production nowadays, a CNC program was chosen as a case study to investigate how the cutting tools are used in terms of tool life and material removal rate, $MRR$.

6.1 Investigation of the CNC program

The CNC program selected for the study was a commonly round shape workpiece where a high percentage of material, in this case HRSA, need to be removed by cutting operations. In the selected CNC program, there was a standard cutting tool, a ceramic insert (RCGX 120700 SIA6060) [67], which was used in 35 occasions that eventually was chosen and scrutinized.

The data corresponding to those 35 occasions where the insert was used was extracted from the complete CNC program and further analyzed. A detailed investigation, together with the results and analysis is appended in Paper B.

The CNC programs provide information about the three-dimensional movement of the cutting tool tip. This can be simplified to a two-dimensional plane ($X$, $Z$) in the case of turning operations. The data provided by the CNC program is the initial and final point of the movement, the cutting speed, the feed, and the depth of cut, used. Thereby, the initial and final point of each single operation was extracted from the CNC program together with the cutting speed and feed used.
By extracting the data provided by the CNC program, row by row, it is possible to split the operations into steps, here referred as single operations. Each insert is used during a sequence of single machining operations.

The spiral cutting length can be calculated, as a simplification, by using Equation (9). Further, the machining time for each single operation can be calculated with Equation (11).

Tool life was calculated with the extended Taylor’s tool life equation, Equation (25), for each single operation. Similarly, the MRR, and the chip volume removed, \( V \), were calculated with Equations (3) and (12) respectively for each single operation.

Finally, \( UTL \) can be calculated as the sum of all the single operations in which the insert is used, Equation (27). Similarly, \( RTL \) can be calculated with Equation (30).

### 6.2 Findings

Every insert analyzed, was used with different feed rates, varying from single operation to single operation. Therefore, the inserts were used at different MRR values. The results of the study were plotted as the unique combinations of cutting speed and feed used throughout the CNC program, including the reference value provided by the tool supplier, represented in Figure 23. Depicted here are the percentages that each of these unique combinations of cutting parameters were used. Figure 23 helps to visualize that the inserts were mainly used above the MRR of the reference combination [67] during approximately 75% of the machining time.

### 6.3 Reasoning of the findings

The selection of the different feed rates with the same cutting speed indicates a selection of cutting parameters towards the mechanical load barrier, Figure 5, of the cutting tool. The use of the inserts in a higher MRR level might represent a higher productivity, but by doing so, the tool life is also negatively affected.

The study also shows how well the tools are utilized. \( UTL \)-values varying from 2% up to 104% are represented in Paper B, Figure 8. For a better visualization of the \( UTL \), the inserts have been reordered from smallest to largest values and
are presented in Figure 24. From this figure, it is possible to deduct that only 20% of the inserts are used above 75% of their expected tool life.

Figure 23: Unique combinations of cutting speed and feed used including percentages and reference values provided by the tool supplier, [93].

Figure 24: Utilized tool life (UTL) for each studied cutting insert reordered from smallest to largest values.
Similarly, $RTL$-values ranging from -4% up to 98% are represented in Paper B, Figure 9. In addition, for a better visualization, the $RTL$ has been reordered from largest to smallest values and are presented in Figure 25. This provide evidence that around 50% of the accumulated tool life, for the 35 inserts studied, are not used and therefore wasted. These tools can be regarded as an unnecessary addition to the total waste.

In addition, there are two exceptions or inserts that have been used above their $ETL$. The use of inserts above its $ETL$ can lead to, e.g., geometrical problems in the workpiece. This can further lead to even greater material waste if the workpiece need to be scrapped. Therefore the use of the cutting tools above their expected tool life must be avoided.

![Figure 25](image.png)

**Figure 25:** Remaining tool life ($RTL$) for each studied cutting insert reordered from largest to smallest values.

If this kind of data; $ETL$, $UTL$, $RTL$; can be accessed while programming, for instance, the operations could be organized in such a way that more operations could be done with the same cutting tool. The benefits are not only increased utilization of the cutting tools but also avoiding unnecessary tool changes and decreasing the amount of tools wasted.

Last, the study was performed on one type of inserts used for the machining of the workpiece. Further analysis of the other inserts used, might bring the possibility to achieve an even greater utilization of the cutting tools and reduction of the total machining time.
7 Integrated optimization algorithm for cutting data selection for longitudinal turning operation

The combination of a tool wear model and iso-$MRR$ curves considering constant depth of cut has been presented in Chapter 3. These curves can allow the CAM Programmer to adjust the cutting data as to optimize the tool's capability with respect to both the Material Removal Rate and cutting tool utilization.

A proper selection of the cutting parameters in a machining operation is a key step to achieve the aimed productivity. Once the workpiece material, the operation and the cutting tool are chosen; the selection of the depth of cut, the feed and the cutting speed is requested. The time required by the CAM Programmer to obtain optimal values can take several iterations. Therefore, an integrated optimization algorithm for cutting data selection has been developed and is presented in this chapter. This aims to help the CAM Programmers during the selection of the cutting data, one of the key steps during the CAM programming workflow by reducing the time and iterations needed during that step. By using this algorithm, it is possible to select the cutting data with respect to $MRR$ and tool utilization, and at the same time, reduce the development time of the NC-program.

7.1 Optimization of the parameters

The optimization of the parameters can be done with respect to different criteria such as maximizing production rate [94-96], minimizing cost [97], maximizing Material Removal Rate [98], or maximizing tool life [99]. In other words, to maximize the amount of parts machined per hour, minimize the total production cost of a part, maximizing the material removal per time unit, or maximize the time in which a tool can be used until it reaches an established wear criteria.

The optimal cutting data values depend on several related parameters, have several constraints and potentially multiple simultaneous optimization criteria. Thus it is difficult to reach a balance between them [100].
In industrial operations, where a high percentage of raw material needs to be removed and the machining time need to be kept to the minimum, $MRR$ is an extensively used objective or criteria. As presented in Equation (3), $MRR$ is a function of feed, depth of cut and cutting speed.

Furthermore, a second criterion is the tool utilization. This criterion will be limited by several constraints. In particular, and specific for the aerospace industry, is the specific tool change point of the cutting tools, which avoid the disruption of the surface finish of the workpiece. Thus, the cutting data need to be selected in order to be able to reach the tool change point without exceeding the tool life and to utilize the cutting tool to its maximum extent.

The integrated optimization algorithm will find the balance between the two criteria of $MRR$ and tool utilization. For instance, in case of increasing $MRR$ it might be possible to reduce the machining time of the operation, reducing as well the tool life, as presented in Figure 26. Further, in case of reducing $MRR$ it might be possible to extend the tool life until the operation is finished avoiding for instance a tool change.

![Figure 26: Balance between MRR and tool utilization.](image)

### 7.2 Description of the integrated algorithm

The integrated optimization algorithm has as input the geometrical and material data from the workpiece and the cutting tool, including the nose radius of the cutting tool, $r_n$; the depth of cut, which is normally considered constant; and the aimed $MRR$. Further inputs are the maximal power provided by the machine,
INTEGRATED OPTIMIZATION ALGORITHM FOR CUTTING DATA SELECTION FOR LONGITUDINAL TURNING OPERATION

\( P_{\text{max}} \), and the machine efficiency, \( \eta \); the maximal spindle speed, \( n_{\text{max}} \), that the machine tool can provide; and the expected \( R_a \). This algorithm is depicted in the appended Paper C, Figure 3.

The initial cutting data work frame for a certain depth of cut is presented in Figure 5. Thus feed and cutting speed values are constraint by the maximal mechanical and thermal load that can be applied on the tool.

Further constraints are the maximal spindle speed that the machine tool can provide, which will further constrain \( v_c \). The maximal power provided by the machine tool and its efficiency will constrain the power required during the cutting, \( P_c \), Equation (8). While keeping the specific cutting force, \( k_c \), of the material constant for the different possible feeds, the maximal power available will therefore provide a constraint on the maximal \( MRR \).

\[
P_c = \frac{f a_p k_c v_c}{60 \times 10^3} = \frac{k_c \cdot MRR}{60 \times 10^3} \leq \eta P_{\text{max}}
\]  

(32)

Another constraint is the expected average surface roughness, \( R_a \), after the cutting operation, Equation (13), which will constrain the feed. To assure the surface integrity, using the nose radius of the cutting tool, \( r_e \), and the expected \( R_a \), the algorithm calculates the maximal value for the feed as in:

\[
R_a = \frac{f^2}{32 r_e} \iff f_{\text{max}} = \sqrt{\frac{32 r_e}{R_a}}
\]  

(33)

The algorithm calculates the machining time, Equations (10)-(11), the iso- \( MRR \) curves, Equation (3), and the Taylor tool life equation constants, Equation (25). Further, the constraints are applied, thus reducing the valid combination area, as represented in Figure 27. The algorithm calculates \( ETL \), \( UTL \), and \( RTL \) as previously described in Equations (26), (27) and (30) respectively. In the case when \( RTL > 0 \), the algorithm will generate a new iteration where the values of feed and/or cutting speed will be increased. Conversely, if \( RTL < 0 \), a new iteration will occur, until \( RTL \) approximates zero.

After several iterations, the algorithm reaches the optimal cutting data combination, which is the one that assure both maximal \( MRR \) and tool utilization. By a series of arrows, Figure 27 represents an example of the path of iterations from the first cutting data combination to the optimal cutting data combination.

Last, as a result, the algorithm extracts the output data as the optimal cutting data combination \( \{v_c, f\} \), \( ETL \), \( UTL \) and \( RTL \).
INTEGRATED OPTIMIZATION ALGORITHM FOR CUTTING DATA SELECTION FOR LONGITUDINAL TURNING OPERATION

Figure 27: Representation of valid combination area for the cutting data with all the limitations included in the integrated optimization algorithm. The arrows indicate an example of the iterations path from the first cutting data to the optimal cutting data combination [101].

7.3 Implementation of the algorithm for longitudinal turning operation

An example of the implementation of the integrated optimization algorithm for the cutting data selection for a longitudinal turning operation is presented as follows.

The initial blank or raw material is a HRSA with a specific cutting force of 2500 [N/mm²], has an initial diameter, $D_0$, of 200 [mm] and a length, $L_z$, of 350 [mm].

The aimed $MRR$ is 50 [cm³/min] and the selected $a_p$ is 2 [mm].

The cutting tool chosen has a nose radius of 1.5 [mm]. The tool wear model is the extended Taylor tool life equation (25) considering the constants $\alpha, \beta, \gamma$ and $C_t$ calculated in Chapter 3.10.1 as 1, 1, 0 and 240 respectively.

The limitations considered are 1000 [rpm] for the maximal spindle speed, 10 [kW] for the maximal power provided by the machine, 90% for the machine efficiency, 20 [µm] for the average surface roughness, and 0% of remaining tool life.
The initial cutting data considered is 130 [m/min] for the cutting speed and 0.2 [mm/rev] for the feed.

For the example, each iteration considers a variation in the cutting speed value of 10 [m/min] and a variation in the feed value of 0.02 [mm/rev]. The initial cutting data and the possible first steps are presented in Figure 28. The algorithm select the one that gives the highest MRR and lowest RTL and use that cutting data for the next iteration, as the path presented in Figure 27, until it reaches the optimal cutting data values.

Figure 28: Example of implementation of the algorithm for longitudinal turning operation. Representation of the first iteration in the search of the optimal cutting data.
8 Drilling process optimization

Every company search for maximum productivity, maximum quality of the products and minimum production cost. In machining operations, such as the drilling process, the previously mentioned objectives are related to the cutting data selected for the operation. In addition, the cutting data is related with the cutting tools utilization. In order to guaranty these objective functions, the use of different resources needs to be optimized, as is the case of cutting tools. Thus, the importance of managing the cutting tools and their use.

8.1 Drilling operation specifics

There are two main specific differences which are characteristic of the drilling process and are required to maintain the finishing and quality of the holes produced. First, the number of holes drilled with each drill bit need to be an integer number. In addition, and in accordance with [102], the expected tool life, the utilized tool life and the remaining tool life of the drill bits can be measured in number of holes, $N_h$.

8.1.1 Integer number of holes drilled

During the planning of a drilling operation, there will be a number of cutting tools available, $N_t$, to machine a number of holes, $N_h$, in accordance with the geometry of the workpiece.

When dividing $N_h$ by $N_t$, the result is the number of holes that each cutting tool need to machine, $M$. The drill bit cannot be changed during the machining of one hole; therefore $M$ needs to be an integer number. However, $N_h$ might not be a multiple of $N_t$, thereby leaving some residue/reminder, $r$, or number of holes that also need to be machined, see Figure 29. When this happen, the amount of holes machined per drill bit needs to be extended by one, to assure that all the holes in the workpiece are machined.
The remaining number of holes, \( r \), is calculated as:

\[
    r = N_h \mod N_t
\]  
(34)

The number of holes machined by each cutting tool can be defined as:

\[
    M = \begin{cases} 
        \frac{N_h}{N_t}, & \text{when } r = 0 \\
        \frac{N_h - r}{N_t} + 1, & \text{otherwise} 
    \end{cases}
\]  
(35)

In case the remaining number of holes, \( r \), is not zero, the new total amount of holes that can be drilled will be greater than \( N_h \). This can be appreciated with the calculation of a new residue/reminder, \( r^* \), which represents an “extension” of the amount of holes that could be drilled:

\[
    r^* = \left( \frac{N_h}{N_t} \right) + 1 \right) N_t - N_h = MN_t - N_h
\]  
(36)

Therefore, if \( r^* = 0 \), all cutting tools are used to their extending tool life, thus \( UTL = 100\% \). If \( 0 < r^* < M \), the last cutting tool is not fully utilized, thus \( UTL < 100\% \). If \( r^* > M \), there will be one or more cutting tool that are redundant, thus unnecessary to perform the drilling operation at hand. In addition, \( UTL \) will be less or equal to 100\%.
8.1.2 Expected tool life, Utilized tool life and Remaining tool life for drilling operations

In the case of drilling operations, ETL, Equation (26), can be translated to the maximum number of holes achieved per cutting tool, M. Furthermore, UTL, Equation (27), can now be expressed as the total number of holes, N_h, divided by the product of the number of cutting tools used, N_t, and the maximum number of holes achieved per cutting tool, M. By the application on Equation (36), UTL can be written as an expression of N_h and r^*, as presented in the following equation. Last, RTL can be calculated by Equation (30).

\[
UTL\% = \frac{N_h}{N_t M} \times 100\% = \frac{N_h}{\frac{r^* + N_h}{N_t}} \times 100\% = \frac{N_h}{r^* + N_h} \times 100\%
\]  

(37)

8.2 Optimization of the drilling process

Several studies have been performed over the last years in machining performance prediction and optimization [103, 104]. Similarly to what has been previously done for longitudinal turning operations [101]. An algorithm for the selection of the optimal cutting data can be applied to drilling operations. When optimizing the drilling operation, maximal MRR, maximal UTL and minimum C_m are aimed. Thereby maximizing the productivity and minimizing the cutting tool life wasted and the machining cost. Thus, to find the optimal cutting data means to find the balance between all the objective functions [105, 106], in this case the MRR, the UTL and the C_m. The optimization problem can be described as follows.

Constants:

There are several constants to be considered, which are dependent on the cutting tool, the workpiece or the machine tool at hand. The optimization of the drilling process considers the following constants: \( a_p, \beta, \gamma, C_t, C_{lab}, C_{mac}, C_{tool}, D_c, f_{mec}, f_{min}, \theta, h, K_f, K_r, k_c, L, MRR_{min}, n_{max}, n_t, N_h, P_{max}, P_t, P_{th}, R_{max}, T_{th}, t_m, t_{tot}, v_{c \text{ therm}}, \) and \( v_{c \text{ min}}. \)
**Decision variables:**

In analogy with other researches [107], the decision variables are the following: $f$, $v_c$, $n$, $N_t$. Note that $n$ and $v_c$ are related by Equation (14).

**Objective functions or criteria:**

The objective functions are maximum $MRR$, Equation (20); maximum $UTL$, Equations (27) and (37); and minimum $C_m$, Equation (31).

**Constraints or limitations:**

The upper variable constraints are the mechanical and thermal barriers, which represent the limitations in terms of maximal mechanical and thermal loads that the cutting tools can sustain; represented as continuous red line in Figure 30.

Other constraints are the maximal surface roughness allowed in the workpiece, the range of values of the spindle speed and the maximal power that the machine tool can provide. The minimum productivity desired in production will also limit the minimum $MRR$ allowed. At the same time, the values of feed and cutting speed will have constraints regarding the minimum values that can be selected, as presented in Paper D.

![Figure 30](image.png)

Figure 30: Representation of the constraints of the process and the feasible region from where the cutting data can be selected.
Optimization:

The optimization is approached by an interactive method, as in the multi-objective optimization. The method will generate a Pareto front, where the Pareto optimal solutions are located. Furthermore, the decision maker, DM, that in this case will be the CAM Programmer, can choose the Pareto optimal solution that will assure the different constraints and limitations and will provide a balance between the different criterion.

8.2.1 Drilling optimization algorithm

In analogy with the algorithm presented in Paper C, Figure 3; here is presented the optimization algorithm for the drilling operation. Initially, the constants, the decision variables and the constraints are selected and defined. Thus, the feasible region, S, can be created. The objective functions are selected and defined. Thereby it is possible to evaluate the different criteria in the feasible region, for instance, the ones presented in Paper D, Figures 9 and 10. Further, the algorithm will search for the Pareto front, which will be provided to the decision maker. Last, the Pareto optimal is selected, as represented in Figure 31.
8.3 Theoretical numerical example

The optimization method proposed is demonstrated through a numerical example. An illustrative example is presented in Paper E. This considers a workpiece having a cylindrical shape, thin wall and a minimum of two flanges where several holes need to be drilled, as represented in Figure 32. This example requires to drill $N_h=121$ drill holes, of diameter $D_c=30$ mm, and depth $L=40$ mm. The number of tools than can be used are $N_t=1 \rightarrow 50$. Further constants and constraints of the example are described in the appended Paper E.

Figure 32: Representation of workpiece example.

8.3.1 Generation of feasible area

The number of cutting tools used influence the non-cutting time, thereby, affecting the total operation time, which will be further multiplied by two additional factors, namely the labour cost and the machine cost. $N_t$ will be directly related to the tool cost, which is dependent on both the cutting tool and the tool holder. The machining cost, expressed as the sum of labour, machine and tool cost as presented in Equation (31), will define an upper limit for the selectable cutting data. Therefore, these limitations will further constrain the feasible set, as presented in Paper E, Figure 6.

8.3.2 Findings on Tool Utilization

The maximum number of holes per tool, $M$, can be the same for several values of $N_t$. $M$ determines the cutting data to use, however, the lowest value of $N_t$ will be the one that provides the highest $UTL$. In addition, $MRR$ and $C_m$ are constant. Therefore, it is possible to detect that the following values of $N_t$ where
$M$ is the same might become redundant, represented and colour coded in Figure 33.

![Figure 33: UTL, MRR and Cm when producing Nh=121 holes with Nt=1-50, as a function of M and Nt. Tool fully used (green), partially used (yellow) and redundant (red).](image)

### 8.3.3 Calculation of objective criteria values

The values of three objective criteria, $MRR$, $UTL$ and $C_m$, can be calculated as a function of the number of tools. The objectives values when $N_t = 1 \rightarrow 15$ are presented in the appended Paper E, Table 1.

As presented in this example, lower values of $N_t$ will yield high values of $UTL$. However, it will result in low values of $MRR$ and high cutting and non-cutting time requirements, thereby increasing the total operational time, which further translate into higher cost. Conversely, higher values of $N_t$ allows an increase in cutting speed. This will maintain high values of $UTL$, and both the $MRR$ and $C_m$ will increase.
8.3.4 Search for Pareto optimal values

A multi-objective optimization approach will provide the Pareto optimal points. The Pareto optimal values are selected from the feasible set with regard to $MRR$, $UTL$ and $C_m$.

The DM or CAM Programmer might be able to take these points into account when making the final decision on the cutting data and number of cutting tools needed for the work ahead, e.g., when an increase of $MRR$ will be more relevant than an increase in cost, thereby finding a balance among all the objective criteria. Thus, the importance of using a multi-objective criteria optimization during the selection of the cutting data.
9 Towards sustainability: energy, CO₂ and water estimation

The energy consumption, CO₂-footprint and water usage during the manufacture of a workpiece can be estimated, as previously mentioned in Chapter 4.

A theoretical study of a feature-based machining operation is presented here, in which total energy use, environmental footprint and cost for a workpiece has been estimated.

The standard engineering software platform, CES Selector with the Eco Audit tool [85], has been used in order to estimate and compare the above mentioned eco-properties. The advantage of this approach is that the database already contains most of the necessary parameters and that these constitute established data used by the aerospace industry [108].

9.1 Workpiece and cutting tool materials

Two Ni-based Heat Resistant Super Alloys, HRSA, are considered as workpiece materials in this study: Inconel 718 [109], and Waspaloy [110]. SiAlONs are ceramics that combine high toughness and hot hardness with good mechanical and thermal shock resistance. Therefore, this type of tool is recommended and used for the machining of HRSA. They allow an even higher cutting speed compared to cemented carbides, thus increasing productivity [54]. Density, price, eco-properties and processing properties for both workpieces and cutting tool materials, are given in Paper F, Tables 2-3 [85].

9.2 Theoretical workpiece manufacturing

A hypothetical workpiece, depicted in Figure 34, is considered as the example in this study. It is cylindrical with two flanges that contain 24 holes each. A flange is used to connect different parts and can be used for different applications such as aerospace, plumbing and piping.
The blank/raw material considered for the production of the workpiece has a solid cylindrical shape with a diameter of 620 mm and a length of 1230 mm.

![Figure 34: Workpiece used as theoretical example.](image)

### 9.2.1 Cutting tool manufacturing

The production of cutting tools usually consists of different steps such as powder processing; weight, mixing and milling; spray drying; compacting; hot pressing; grinding and coating [54]. Here, the eco-properties for the primary production of the SiAlON material and grinding processing are taken into account.

### 9.2.2 Machining processes

Several cutting operations are needed during the machining of the workpiece. The cutting operations are divided into rough and fine machining, which allow removing material as fast as possible, and achieving the geometrical and surface requirements of the workpiece, respectively. Material removed by rough machining operations, rough turning and drilling, are marked as dark grey in Figure 35. Similarly, all the fine machining operations, fine turning and reaming, are marked as light grey. This distinction is needed due to the available processing options, as given in Paper F, Table 2.

The dimensions of both blank and workpiece are presented in Figure 35. A simple volumetric calculation shows that 29% of the material is removed from the blank material during rough machining operations. Similarly, 1% of the
material is removed by fine machining operations. The volumes of material removed in each cutting operation are presented in Paper F, Table 4.

In addition, this workpiece can, for instance, be machined in three tempos. First a rough turning operation is used to flatten the surface. Then, the workpiece can be considered as two symmetric halves that both include all of the features. These are machined in two tempos which each will include rough face and longitudinal turning, finishing face and longitudinal turning, drilling and reaming operations.

![Figure 35: Illustration of the cutting processes, separated into rough machining (dark grey) and fine machining (light grey). Workpiece dimensions in [mm].](image)

In the theoretical example, the density values selected are taken to be 8220 [kg/m³] for Inconel 718 and 8250 [kg/m³] for Waspaloy, resulting from the arithmetical average between the minimum and the maximum values in the database for each workpiece material. This results in a total mass for the raw materials of 3052 kg for Inconel 718 and of 3063 kg for Waspaloy.

### 9.3 Findings

The average energy consumption during mining and primary production (embodied energy) of Inconel 718 is higher than for Waspaloy by 17%, according to the database and using the Eco Audit. Note that the values are
dependent on the fraction of recycled material in the feedstock, assumed to be zero in the example. One should be aware that the uncertainty of environmental data can be as much as 20% [85].

The approximate range of values estimated for the workpiece using the database are presented in Table 4.

Table 4: Production and processing energy, environmental footprint and water usage for the workpiece materials used in the theoretical example.

<table>
<thead>
<tr>
<th>Material: Ni-based super alloys (HRSA)</th>
<th>Inconel 718, Ni-Cr alloy, Solution treated &amp; aged</th>
<th>Waspaloy, Ni-Cr alloy, Precipitation treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>General properties (x10³):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass [kg/workpiece]</td>
<td>3.052</td>
<td>3.063</td>
</tr>
<tr>
<td>Eco properties, Primary production (Energy, CO₂ and water) (x10³):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Embodied energy [MJ]</td>
<td>888 – 979</td>
<td>738 – 814</td>
</tr>
<tr>
<td>CO₂ footprint [kg]</td>
<td>50 – 55</td>
<td>39 – 43</td>
</tr>
<tr>
<td>Water usage [l]</td>
<td>717 – 790</td>
<td>1000 – 1105</td>
</tr>
<tr>
<td>Processing properties (Energy, CO₂ and water) (x10³):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough rolling, forging CO₂ [kg]</td>
<td>1.8 – 2</td>
<td>1.7 – 1.8</td>
</tr>
<tr>
<td>Rough rolling, forging water [l]</td>
<td>15 – 23</td>
<td>14 – 21</td>
</tr>
<tr>
<td>Rough machining energy [MJ]</td>
<td>1.4 – 1.6</td>
<td>1.3 – 1.5</td>
</tr>
<tr>
<td>Rough machining CO₂ [kg]</td>
<td>0.11 – 0.12</td>
<td>0.1 – 0.11</td>
</tr>
<tr>
<td>Fine machining energy [MJ]</td>
<td>0.3 – 0.4</td>
<td>0.34 – 0.37</td>
</tr>
<tr>
<td>Fine machining CO₂ [kg]</td>
<td>0.02 – 0.03</td>
<td>0.02 – 0.03</td>
</tr>
</tbody>
</table>

Energy estimation:

The energy for workpiece processing, including rough rolling or forging and the rough and fine machining, are 30 times smaller than the embodied energy. Processing properties are presented separately in Figure 36. Data from this diagram, supports the trend that the level of energy use related to Inconel 718 is higher than that for Waspaloy.
Cost estimation:

The amount and price of the material needed per workpiece will influence the cost greatly. If only the average estimates of the material price shown in Table 4 is considered, Waspaloy is 36% more expensive.

$CO_2$-footprint estimation:

In analogy to the energy use, the $CO_2$-footprint associated with the materials follow the same trend and is 28% higher for Inconel. The emissions from both rough and fine machining of Inconel 718 are also higher than those resulting from Waspaloy, as presented in Figure 36.

Water usage estimation:

The water usage estimation, [111], for the material Inconel 718 is considerably lower than for Waspaloy during the primary production. The water usage for rough rolling is some 30-40 times lower than primary production as shown in Figure 36.

Figure 36: Energy, $CO_2$—footprint and water usage estimation for manufacture of the theoretical workpiece in both Inconel 718 and Waspaloy [112].
Cutting tools:

A more detailed study was performed for the production of the cutting tools needed, taking into account the recommended cutting data [113], such as cutting speed 250 m/min, depth of cut 2 mm and feed 0.2 mm/rev as well as an estimated tool life of 15 min. It is possible to estimate the spiral cutting length that the cutting tool will accomplish, for the theoretical example presented in Figure 34. Furthermore, this length can be translated into the machining time needed for each operation. Both materials, Inconel 718 and Waspaloy, have similar machinability. Hence, it is assumed that the cutting tools will wear off at a similar rate. Considering that the cutting tools will be used to their full extent of their tool life, it is possible to estimate that the number of inserts needed for the machining operations are around 82. Note that no other parameters such as the cutting tool changing point is taken into account. Therefore, this represents the minimum number of inserts needed.

The energy use during the primary production of insert material (SiAlON), estimated in this way, is 90 MJ whereas the energy required for grinding processing is around 4 MJ. These values are minute in relation to the workpiece itself with, in this case, four orders of magnitude higher embedded energy.

The environmental footprint of the cutting tool material follows the same trend as for the energy. The total CO$_2$--footprint emission are 5 kg and 94 l of water usage during the primary production of cutting tools, which is considerably less than for the workpiece.
III. CONCLUSIVE CHAPTERS

10 Analysis

This chapter presents the analysis of the main areas of this work. In addition, it addresses the research questions presented in Chapter 1.

10.1 Analysis of the CAM programming work flow

In order to answer the first research question \((RQ1: \text{How do CAM Programmers conduct the CAM programming process?})\) in Chapter 1.3 and get an understanding of how the CAM programming process is conducted, CAM Programmers were interviewed. They were asked to explain their work flow step by step. Using data recollected from the interviews and the experience of the author, a CAM programming work flow was created, as presented in Appendix B. The interviewees had different ideas about the projects and their involvements were significantly different. Interviews were also used to confirm that the work flow was similar to the one presented in Figure 2. For the Lean study, however, more details were needed.

Once a detailed CAM programming work flow was constructed, it was analyzed from the Lean perspective. Lean was used to identify possible inefficiencies in the CAM programming flow, as an answer to the second research question \((RQ2: \text{What kinds of inefficiencies exist in the CAM programming process from the Lean perspective?})\) proposed in Chapter 1.3. This study showed that there were several key steps agglomerated into two areas, see Paper A, Table 1. One area consisted of the process, machine, cutting tool and clamping system selection during the process planning. The other area concerned the operation definition, the machining parameters selection, the tool path generation and the simulation and verification during the NC program development.

Furthermore, during the development of the NC program, several iterations are needed for the optimal selection of the cutting data, the definition of the different operations, the generation of the tool path and its simulation and verification. The estimated time required for the CAM programming within a
project might include time for iteration. However, every project will manufacture a different component. Thus, the time estimates for the whole process will be rough approximations. The excessive iterations or steps back along the flow, as presented in Appendix B, is normally not included in the time plan and might therefore result in unwanted project delays. Every new project will raise new issues with the corresponding delays. From the Lean perspective, all the excessive iterations needed for the generation of the tool path, can be seen as unnecessary and therefore a waste. If a correction is needed in one of the later steps, the delay generated will be greater than a correction needed in one of the earlier.

The development of software features to simplify the CAM Programmer’s work need to focus on key steps that require large amounts of time and experience. Several improvements to the software can be proposed in order to simplify and reduce the programming time, and to keep gained knowledge within the company. Future software also needs to provide the possibility to simulate and verify as closely to reality as possible, thereby decreasing the need for excessive real tests in the machine. This is related with other researches who suggested that only through technological support can the CAM Programmers reach their full potential as strategic decision makers [114].

The study of the CAM Programming process revealed the experience and knowledge required by the CAM Programmers. They need to have considerable knowledge of the processes, the machining of different materials, the cutting tools, the cutting data selection, the availability of the machine tools, and the logistics. In addition, the CAM Programmer needs to be able to calculate roughly the machining times and costs, which can present a challenge to a new project. Thereby, the third research question was formulated and studied (RQ3: What is the role of the CAM Programmer in the CAM programming process?). The CAM Programmers were identified as “Efficient Islands”. Thus, two different organizations are presented as an initial step towards the “Perfect state”.

Research has found that both technological and organizational improvements in any company contribute to better overall performance [90]. Therefore, two approaches are suggested to continue improving the CAM programming flow, as represented in Figure 37. The first approach is technological with development and improvement of software. One possibility that has been described in this thesis is the integrated optimization algorithm for cutting data selection. The second approach is organizational, with two different proposals to reorganize CAM Programmers.
10.2 Cutting tool utilization in production

A study of a CNC program from the MRR and tool life perspectives was conducted in order to evaluate how well the cutting inserts are used in a production environment.

As an answer to the fourth research question (RQ4: How are the cutting tools used in production with respect to tool utilization?) proposed in Chapter 1.3, it was found that frequently, the majority of the inserts were utilized far below their tool life limit, Figures 24-25. The inserts are not used to their limits of Material Removal and expected tool life. Since those cutting tools are not used efficiently, they can be seen as an addition to the total waste.

The inserts with low or even negative RTL values could be used at lower MRR values by decreasing either the cutting speed and/or the feed, illustrated in Figure 38. By doing this, the effective cutting time will increase, UTL decreases even though it is kept as close to ETL as possible to ensure that the process stability and the surface roughness of the component produced are not affected.
The inserts with high \textit{RTL} values could be used at a higher \textit{MRR} value by increasing the cutting speed and/or the feed rate, as presented in Figure 39. Another option would be to combine and re-order the operations during the CAM programming process. Thus, each insert can be used in additional consecutive operations. In this way, it is possible to reduce the machining time; increase the \textit{UTL} and keep \textit{RTL} closer to zero, ultimately increasing the volume of material removed per insert. Other possible benefits are, for instance, the reduction of tool changes and thereby the elimination of non-cutting time. In addition, the reduction of the number of cutting tools used for the machining of the component can be translated to reduction of tool waste and tool cost as well as the energy needed for the production of the cutting tool.
Even in non-consecutive operations, the operations could be re-ordered during the CAM programming process to enable use of the tool to its maximal extent.

Implicit in the descriptions above is the need for an algorithm to help the CAM Programmer to optimize the use of each insert and reduce the amount of RTL that is thrown away.

10.3 Algorithm for cutting data selection

As an attempt, both to assist the CAM Programmers during the cutting data selection, and to assure the optimal utilization of the cutting tools, an algorithm for cutting data selection was developed for different cutting operations and has been presented in Paper C, D and E, as the answer to the fifth research question (RQ5: How can the cutting data selection be optimized during the tool path generation?).

Maximal \( MRR \) is one of the objectives for a company that seeks to increase productivity. \( MRR \) is dependent on the feed, the cutting speed and the depth of cut. In addition, their combination will set up the working \( MRR \) level, as represented in Figure 5. Note that a different combination of cutting data will achieve different values of \( MRR \), while at the same time the cutting tools will wear off in different rates [101].

The integrated optimization algorithm for cutting data selection can be formulated in analogy with other researches [107]. The algorithm, as presented in Paper C, has two objectives. The first one is to maximize the \( MRR \), as in Equation (3). The second objective is to maximize \( UTL \), as in Equation (27); or equivalently, minimize \( RTL \) as in Equations (29)-(30).

The initial constraints are related to the mechanical and/or thermal load barrier that the cutting tool can sustain, as presented in Figure 5. Their use above these barriers could degenerate them into early brittle and/or thermal failure. Below these constraints, the tool wear will appear gradually and its flank wear can be measured, as presented in Figures 10 and 14. \( VB_n \) is the tool wear criteria limit that will establish the constraint on tool life, \( T \) or \( ETL \), calculated as in Equation (26).

In addition, the range of available values of spindle speed in the machine tool will constitute limitations to the values of the cutting speed. Similarly, the maximal power provided by the machine tool will constitute limitations to the feed and cutting speed values. The desired surface roughness will be a limitation
to the feed values. Furthermore, from the production point of view, there will be a lower limit for $MRR$.

Lastly, as presented in Figure 27, these constraints need to be more restrictive than the initial constraints presented in Figure 5, ensuring that the cutting tool will wear continuously and not present an early failure.

10.3.1 Tool wear calculation

The CAM Programmers might not have access to the expected tool life of the cutting tools, depending on the different cutting parameters. A tool wear equation can then be used, for instance, the mathematical models by Taylor [40], Colding [4], Usui [63] or Takeyama and Murata [62], among others.

The tool wear can be modelled numerically by $ETL$, as presented in Equation (26). Thus, the usage of the cutting tools can be programmed and simulated. However, the values of the Taylor coefficients might not be available for the combination of workpiece material – cutting operation – cutting tool (including material, geometry and coating) – cutting fluids used. Therefore, these coefficients might need to be determined quantitatively.

10.3.2 Algorithm extension for drilling operations

Three objective criteria have been considered for the algorithm extension for drilling operations, i.e., $MRR$, $UTL$ and machining cost.

The optimization problem for cutting tool utilization in drilling operations presents several constants, as presented in Chapter 8.2.

In addition to the constraints already presented for the algorithm, drilling operations need to be taken into account another limitation: the number of holes drilled by each cutting tool needs to be an integer value.

The feed, cutting speed, spindle speed, and number of cutting tools available directly affect the objective functions. The influence of these decision variables is explained in the appended Paper D.

Other functions, both as objectives and constraints, could be included in the optimization of the machining process. The inclusion of new limitations could
reduce the feasible region. However, the search of the Pareto optimal solutions could become more complex.

10.3.3 Path towards the optimal cutting data combination

The initial cutting data combination used in the iterations is normally provided by the tool supplier, otherwise, it can be selected by an experienced CAM Programmer. In the search of the optimal cutting data combination, the variables that are modified are the feed and/or the cutting speed, which correspond to the two variables that the operator can adjust on the machine.

As represented in Figure 40, a variation in the cutting data can lead to a new combination that could be positioned in the same iso-\( MRR \) curve. The same productivity will be maintained, however, the tool life will vary along the curve. Another option is that the new combination will be positioned at a different iso-\( MRR \) value. In the case that the new position is in a lower iso-\( MRR \) curve, the machining time and the tool life might increase. This brings the opportunity to extend the tool life until the operation is finished and to reduce the total machining time by decreasing, for instance, the number of tool changes. In the case that the new position is at a higher \( MRR \) value, the machining time and the tool life might decrease. Thereby, providing the opportunity to reduce the total machining time by decreasing the machining time and, as a consequence, increasing the productivity.

![Figure 40: First cutting data combination point and possible variations.](image)
10.3.4 Cutting tool utilization

The cutting tool needs to be utilized to its maximum extent; however, the cutting tool must be changed at specific points due to surface finishing requirements. Therefore, as a consequence, the cutting data needs to be selected so as to reach the tool change point without exceeding the tool life. The balance between maximum productivity and minimum waste is sought. Thus, if more material can be removed with each tool, less remaining tool life will be thrown away as waste.

Moreover, other researchers [115] have presented interesting ways to improve the cutting tool utilization, which can be implemented in the ongoing search for increased production rate and decreased energy consumption.

10.3.5 Pareto optimal selection

In order to select the cutting data that will provide the optimum among several objective functions, a multi-objective optimization process is commonly used. Here, the case where material removal rate, utilized tool life and machining cost were used as objective functions has been presented. The optimization process will define the feasible area, evaluate the objective functions within that area and identify the Pareto front, as presented in the appended Paper E. Furthermore, the decision maker will select the Pareto optimal values from the Pareto front. Thus, answering to the sixth research question \( RQ6: \text{How to select the cutting data for a drilling operation that will assure maximal MRR, maximal UTL and minimum } C_m \)?

10.4 Sustainability

Companies that want to be competitive need to keep focus on their employees, such as Operators, CAM Programmers, etc. They need to encourage continuous learning, integration in the company, promote health, trust and respect from the company to all the employees. This will lead to positive consequences; creating a socially sustainable working environment, which will also impact the society outside/around the company.

Researchers have pointed out that new strategies will take into account not only the company and the customers, but also externalities such as the environment
[73] in business models. Several factors and perspectives influence eco-design and sustainable manufacturing, such as political-legal, scientific and business perspectives. These perspectives will create the framework to develop new products from an improved sustainability standpoint [116].

From the sustainability perspective, and since materials resources are limited, it is important to keep in mind how efficiently each kilo of material is extracted, manufactured and further utilized; including the prospect of their end-of-life activities, such as Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture (6R).

### 10.4.1 Machining process sustainability

The manufacture of a product or component requires several manufacturing processes, for instance forming, machining, welding and assembly. According to previous research [81, 117], several factors should be taken into account: the work material, the cutting tools, the energy used, the water consumed, the finished products, the chips generated, the used cutting tools, the used coolant, the mist or leaks, the scrap or defects, the emission, the noise and other residues. In order to evaluate the sustainability of those processes, the energy used, the cost, the CO₂-footprint, and the water consumed can be estimated, which, at the same time, provide an answer to the seventh research question proposed in Chapter 1.3 (RQ7: Which objectives can be considered to estimate the sustainability of a manufacturing process?).

Furthermore, a description of how to estimate the energy used, the cost, the CO₂-footprint and the water used is presented in Chapter 4. Chapter 9 and appended Paper F adds to this description with an example of the manufacture of a theoretical workpiece. Thus, answering the eighth research question by providing a simple but realistic estimation manner (RQ8: How to estimate, in a simple but realistic manner, the energy use, the CO₂-footprint and the water use during the manufacturing of a workpiece?).

### 10.4.2 Advances towards sustainability

The use of coolants/lubricants can have both positive and negative effects on sustainability. It can extend the life of cutting tools. However, energy is required to provide the desired pressure in the cutting zone, the workpiece needs to be cleaned after machining, its reutilization might be limited, and its disposal could
harm the environment. Furthermore, the coolant/lubricant gradually dilutes during the machining process in form of mist, leaks, and adsorption in the chips [118].

In the case of machining processes, coolants/lubricants are one of the main causes of environmental pollution [35], hence their importance during the machining process and the end-of-life activities. However, recent advances in sustainable coolants/lubricants can help to reduce environmental emissions and consumption of natural resources, to reduce health and safety risks as well as to improve economy and performance [119].

The cutting tools and the selected cutting data directly impact the generation or unnecessary waste material. The use of cutting tools not reaching their expected tool life, will create waste. However, the use of the cutting tools above their expected tool life, can damage the workpiece, thereby creating more waste in terms of material that needs to be scrapped and energy.

It is possible to see excessive waste as an extra cost: cost of material, the operators, machines, energy used [120, 121], CO₂-footprint [122], water, coolants, etc; which have direct negative impact on the sustainability objectives of the company, mainly economic and environmental.

Residues and other emissions such as CH₄, N₂O, etc, are factors also affecting the global warming potential [123], which is currently of high relevance in terms of the machining process.

10.5 Industrial implementation of the algorithm

The integrated optimization algorithm for cutting data selection is actually under development for industrial implementation. The objective is to integrate the algorithm into existing CAM systems to support the CAM Programmer during the cutting data selection. Figure 41 shows an example of how the algorithm can be seen by the CAM Programmer in its industrial implementation in an existing CAM system. At this stage of the project, when the CAM Programmer defines the cutting operation, the system can calculate and present to the DM the optimized cutting data in terms of cutting tool utilization or manufacturing cost.
Figure 41: Example of the algorithm for industrial implementation in an existing CAM system.
Conclusions

A study of the CAM programming preparation process has been performed and presented. First, semi-structured interviews to CAM Programmers were carried out in order to investigate how the CAM Programmers conduct the CAM programming process. From this investigation, the CAM programming work flow has been described with enough detail so as to be able to perform an analysis from the Lean perspective. Thereby this investigation allowed the identification of the key steps and the inefficiencies along the work flow.

The key steps identified in the CAM programming process from the Lean perspective can be grouped into two areas. One of the areas where the key steps are identified has a greater success potential by organizational improvements. Accordingly, two new organizational proposals have been presented. The other area where the key steps are identified is more technically oriented and therefore a new algorithm for cutting data selection has been presented.

A study of a CNC program from the MRR and the tool life perspective was conducted in order to evaluate how well the cutting inserts are used in a production environment. It was frequently found that the majority of the inserts were utilized far below their tool life limit, on average approximately 50%. Therefore, those inserts can be seen as an addition to the total waste.

In order to ease the CAM Programmer work, and specific for longitudinal turning operations, an integrated optimization algorithm for cutting data selection based on maximal MRR and tool utilization has been presented. Even thought the algorithm presents several simplifications; it is a means, with which the CAM Programmer can know the remaining tool life, RTL, on the cutting tool. At the same time, the algorithm allows the CAM Programmer to visually understand the relationship between the cutting data selected and both MRR and T. Therefore, the selection of cutting data parameters can be oriented towards productivity and help to better plan the several tool changes required.

Further development of the algorithm has been done concerning drilling operations. First, two objective functions are considered: material removal rate and utilized tool life. Further, the machining cost has been added as a third objective function.

A methodology to manage cutting tools, in this case the drill bits, in an optimized manner has been proposed. The methodology presented here can
help the CAM Programmers to reduce the amount of time and trials during the selection of the cutting data for drilling operations. In addition, the approach can be extended and further applied to other operations.

Different combinations of tool and workpiece materials, workpiece geometry and machine tools used, among others, provide limitations and constraints to establish the feasible area. It has been demonstrated that three objective criteria: maximal $MRR$, maximal $UTL$ and minimum $C_m$ can be assured by using a multi-objective criteria optimization in order to find the optimal cutting data combination. The Pareto optimal solutions balance the material removal rate, the utilized tool life and the machining cost, which can be presented instantly to the CAM Programmer or decision maker. Thereby the selection of the number of cutting tools and the optimal cutting data can be facilitated.

Additional criteria can be considered, which can guide the machining process towards a more sustainable one. For instance, the energy use and the environmental footprint. In this work, a comparison between two materials for a hypothetical workpiece was made. This resulted in a simple but realistic estimation of the theoretical energy use, the cost and the environmental footprint that can aid decision-making.

This type of study can be useful to estimate the environmental impact of the production of any workpiece and might help manufacturing companies to develop a more sustainable production with lower environmental footprint.
12 Discussion and Further work

A short discussion of the conclusions and further work is presented in this chapter.

12.1 Discussion

According to Lean theory, every process has inefficiencies that can be identified and therefore reduced and/or removed only when made visible. After a thorough analysis of the CAM programming process from the Lean perspective, several key steps are identified, which can be grouped in two areas. The trend until now is that the existing problems may be solved by further software development and reorganization. Thus, the use of both technological and organizational improvements leads to a better overall performance of the company.

A study of a CNC program showed that the cutting tools, in this case inserts for turning operations, were utilized below their tool life limit. Therefore, those cutting tools can be seen as an addition to the total waste. When programming, \( UTL \) need to be kept as close as possible to \( ETL \). When reaching low or even negatives values of \( RTL \), the cutting data can be changed to a lower \( MRR \). On the other hand, when reaching high values of \( RTL \), the cutting data can be changed to a higher \( MRR \) level, or reorder the operation to fully utilized the cutting tools.

Software improvements need to be made towards a user-friendly environment, e.g., adding features that will simplify the work of the CAM Programmer. These features can, for instance, give the possibility to visualize and allow the modification of the different variables.

In order to ease the CAM Programmer’s work, an integrated optimization algorithm for cutting data selection based on maximal \( MRR \) and tool utilization has been presented, which is specific for longitudinal turning operations. Thus, the selection of cutting data parameters can be oriented towards productivity and better plan the several tool changes required. It is then possible to provide the CAM Programmer with optimal cutting data, reducing the number of needed iterations to reach the desired level of productivity and, thus, reduce the time required for the development of the NC program as well.
Further extension of the algorithm has been made, specifically for drilling operations, and has been presented here. Initially, both material removal rate and tool utilization were considered. However, machining cost was added as well as a third criterion. When considering several criteria, the selection of cutting data becomes more complex. Here, a methodology is presented, based on multi-objective optimization, which can help the CAM Programmer during the selection of cutting data. Using this methodology, only the Pareto front is presented to the CAM Programmer or Decision Maker, to choose the optimal Pareto values, instead of the whole feasible area.

Exploring the possibility to extend the algorithm even further, the sustainability of the manufacturing processes could be investigated. As an initial evaluation of the sustainability, the energy used, the water consumed and the CO$_2$-footprint created during the manufacture of a component were estimated and has been presented here.

To summarize, as a result of this work, it is possible to improve the cutting tool utilization. Thereby, increasing the amount of material removed per cutting tool as well as decreasing the remaining tool life of the cutting tools, the number of tool changes, the machining time and the number of tools used. In addition, it is possible to decrease the CAM programming work by reducing the number of iterations needed. Thus, by better utilization of gained knowledge, the development time of the CAM programs for new projects can be reduced. Furthermore, the cutting tools can be managed in an optimized manner, which brings benefits in terms of productivity, quality, cost and sustainability.

### 12.2 Further work

In Figure 42, future work is proposed as a continuation of the work presented here.

The integrated optimization algorithm has several simplifications that might need elaboration. For instance, the specific cutting force of the materials varies as a function of feed. The temperatures generated during cutting, the energy dissipated as heat and the use of cutting fluids; even the engagement and retraction of the tool, can benefit or deteriorate tool life. Further development of the optimization algorithm by including other relevant variables is also proposed as future work.

The simplifications introduced, the way the problem is studied, its optimization, the input data and even the initial cutting data combination will affect the
validity of the proposed algorithm. Therefore, verification and validation of the algorithm is needed and is proposed as future work.

In addition, the sustainability of manufacturing processes will need to be taken into account in the future. Therefore, further investigation is proposed in this area.

Figure 42: Schematic representation of present and future work.
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A System of equations for the calculation of extended Taylor Tool Life equation constants

The extended Taylor tool life equation, Equation (25), takes into account the cutting speed, \( v_c \), the feed, \( f \), and the depth of cut, \( a_p \). Furthermore, \( \alpha, \beta, \gamma \) and \( C_t \) are related to the contribution from each parameter to the tool life, \( T \).

First, four “working points” need to be recollected from empirical catalogue data points provided by the tool supplier or the own company experience; namely: 1, 2, 3 and 4. Thus the initial system of equations is the following:

\[
\begin{align*}
& v_{c1} T_1^a f_1^\beta a_{p1}^\gamma = C_t \\
& v_{c2} T_2^a f_2^\beta a_{p2}^\gamma = C_t \\
& v_{c3} T_3^a f_3^\beta a_{p3}^\gamma = C_t \\
& v_{c4} T_4^a f_4^\beta a_{p4}^\gamma = C_t
\end{align*}
\] (A.1)

Second, it is possible to convert these equations from non-linear to linear by taking logarithm in both sides of the equations. Therefore the system of equations will be the following:

\[
\begin{align*}
& \log v_{c1} + \alpha \log T_1 + \beta \log f_1 + \gamma \log a_{p1} = \log C_t \\
& \log v_{c2} + \alpha \log T_2 + \beta \log f_2 + \gamma \log a_{p2} = \log C_t \\
& \log v_{c3} + \alpha \log T_3 + \beta \log f_3 + \gamma \log a_{p3} = \log C_t \\
& \log v_{c4} + \alpha \log T_4 + \beta \log f_4 + \gamma \log a_{p4} = \log C_t
\end{align*}
\] (A.2)
This system of four linear equations can be reordered as follows:

\[
\begin{align*}
\alpha \log T_1 + \beta \log f_1 + \gamma \log a_{p1} - \log C_t &= -\log v_{c1} \\
\alpha \log T_2 + \beta \log f_2 + \gamma \log a_{p2} - \log C_t &= -\log v_{c2} \\
\alpha \log T_3 + \beta \log f_3 + \gamma \log a_{p3} - \log C_t &= -\log v_{c3} \\
\alpha \log T_4 + \beta \log f_4 + \gamma \log a_{p4} - \log C_t &= -\log v_{c4}
\end{align*}
\]  

(A.3)

Further, the system of equations can be written in matrix form:

\[
\begin{pmatrix}
\log T_1 & \log f_1 & \log a_{p1} & 1 \\
\log T_2 & \log f_2 & \log a_{p2} & 1 \\
\log T_3 & \log f_3 & \log a_{p3} & 1 \\
\log T_4 & \log f_4 & \log a_{p4} & 1
\end{pmatrix}
\begin{pmatrix}
\alpha \\
\beta \\
\gamma \\
-\log C_t
\end{pmatrix}
= 
\begin{pmatrix}
-\log v_{c1} \\
-\log v_{c2} \\
-\log v_{c3} \\
-\log v_{c4}
\end{pmatrix}
\]

(A.4)

Last, \(\alpha, \beta, \gamma\) and \(C_t\) can be calculated, for each specific combination of cutting operation-work material-cutting tool used as follows:

\[
\begin{pmatrix}
\alpha \\
\beta \\
\gamma \\
-\log C_t
\end{pmatrix}
= 
\begin{pmatrix}
\log T_1 & \log f_1 & \log a_{p1} & 1 \\
\log T_2 & \log f_2 & \log a_{p2} & 1 \\
\log T_3 & \log f_3 & \log a_{p3} & 1 \\
\log T_4 & \log f_4 & \log a_{p4} & 1
\end{pmatrix}^{-1}
\begin{pmatrix}
-\log v_{c1} \\
-\log v_{c2} \\
-\log v_{c3} \\
-\log v_{c4}
\end{pmatrix}
\]

(A.5)
B Description of the CAM programming workflow

A detailed description of the CAM programming process, constructed from the interviews to CAM Experts is presented as follows. During every project, the CAM Programmer has access to initial drawings/models; including the raw material selected and the expected tolerances; in order to generate initial programs and, at the same time, detect possible production problems. Thus, it is possible for the CAM Programmer to influence somewhat along the design process, on dimensions, tolerances, etc.

There are three systems used along the CAM programming flow: a CAM software for programming, simulation and verification, a definition software and a secondary simulation and verification software.

Note that from Figure B.1 to B.3, a grey scale has been used to differentiate the steps that belong to the different stages of design, process planning and manufacturing; similarly to what was presented in Figure 2. The symbols used in the process flow represented in Figures B.1 to B.3 follow the notation as in [91]. The numbering in the figures is explained in more detail below.

The initial input of the CAM programming flow is the CAD model or design, represented in Figure B.1.

1. The first step for the CAM Programmer is the interpretation of the drawing or model of the component.
2. The blank or raw material dimensions are selected and as an outcome the blank model is created. This step will determine the amount of material to be removed, thereby its importance.
3. The processes to be used are selected and this selection is also an outcome from the process. Productivity is determined by the processes selected, which are divided into the main processes, such as turning, milling and drilling.
4. The machines to be used are selected. Several iterations are needed during this step in order to check not only the machine availability, but also the machine capability or if there is a need to look for other processes.
5. Two parallel flows need be started at this point because both of them normally take several weeks. They are considered as secondary flows.
because the CAM Programmer only supervises them, however, the interaction with other stakeholders is essential.

a. One of the secondary flows is the tool selection and information from previous projects, suppliers, experienced people and the CAM Programmer’s own experience is needed. First, several Tool Suppliers are contacted and one selected. The tool suppliers offer a considerable and useful help to select the right tool for each process and also the recommended cutting data for the operation. The tool manufacturers’ recommendations about tool life are followed, with a security margin criterion.

In the case that there is a standard tool that can be used, that tool is selected. However, in the case that there is no suitable standard tool available, a special tool can be selected. The supplier defines, develops and tests the tool. Once the tool is selected, either standard or not, a purchase order is issued and the tool model is obtained as an outcome.

b. The other secondary flow is the clamping system selection where information from previous projects, experienced people and the CAM Programmer’s own experience is needed. Once the processes are roughly selected, including decisions on the number of tempos, the clamping system can be defined, generated and once approved, fabricated. The clamping model is obtained as outcome.

All the different models for the cutting tools, cutting tool holders, blank, machine tool and clamping system need to be defined in the definition software that is also used for traceability reasons. This is done by the CAM Programmer and it is required before importing those models together with the CAD model in the CAM software for programming, simulation and verification.

6. Since the previous step might take several weeks, a second interpretation of the models or drawings is performed at this point, as represented in Figure B.2.
7. Based on the requirements of each part, the processes selected and the process definitions need to be taken into the CAM system for each main process, such as turning, milling and drilling.
8. Based on the requirements of each part, the selected operational machine model is imported and defined in the CAM system.
Figure B.1: Detailed CAM programming flow Stage 1: Process Planning Stage.
9. The blank and the workpiece models are imported in the CAM system.
10. The selected clamping model is imported in the CAM system.
11. The models of all the selected tools are included in the CAM system. Once all the necessary information is included in the CAM system and using additional knowledge gained from previous projects, know-how from suppliers, experienced people and the CAM Programmer’s own experience, the operations can be defined.
12. When starting to define the operations, it is very common to generate different kinds of operations and tools, in order to compare and select the best one for each step of the machining process. Therefore, this step might take several iterations, as represented in Figure B.3.
Figure B.3: Detailed CAM programming flow Stage 3: CAM programming Stage.
13. Machining parameters need to be selected for each operation such as cutting speed, feed, depth of cut and tool angles. The cutting data provided by the CAM program and/or the tool supplier is considered as the starting point. The CAM Programmer looks for minimum tool wear, minimum production time and maximum productivity. Further, the CAM Programmer performs several trials in order to find the parameters that will allow a better use of the tools, and set up tool change points in appropriate locations to reach the required tolerances. Therefore, the selection of the optimal cutting data might take several iterations.

14. Once the operation is defined and the machining parameters are selected, the tool path is generated, which represents the path that the tip of the tool will follow while machining. This step may also take several iterations, as represented in Figure B.3.

15. Once the tool path is generated, the CAM Programmer starts a series of simulation and verification operations that range from simple to more complex ones. If an issue is encountered at this step, it is corrected by reversing to the operation definition and the machining parameters selection steps.

16. Next, the CAM Programmer orders the operations in the production sequence.

17. The CAM Programmer creates a measuring program, used for quality assurance during production, by allowing the geometrical inspection of the component along the production processes.

18. The CAM program is post-processed and converted into the corresponding machines-specific language.

19. Specific for aerospace components, simulation and verification using a second software is required. The aim of this step is to ensure that all the tests, as near as reality as possible, have been performed before a real production test. In the case of encountering an issue at this step, it is needed to go back to the necessary step in the first software and adjust the part program.

20. Once the simulations and verifications are passed, a real test at the machine is performed. After a real test part is manufactured, the test part is inspected and approved in terms of dimensions, tolerances, etc. Small adjustments might be needed in the program to reduce the effect of vibrations of the machine or excessive tool wear among other phenomena. Once this test is passed, the program can be “frozen” and sent to production.

21. The inspection of the first approved component from the production defines the closing step in the CAM programming flow.
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On Cutting Tool Resource Management

The thesis proposes means to aid forward looking manufacturing companies search for increased productivity and cost reduction, interpreted as the maximization of Material Removal Rate, the maximization of cutting tool utilization and the minimization of the machining costs. The CNC process is complex and involves numerous constraints and parameters. A well-managed preparation process creates the foundation for achieving a reduction in manufacturing errors and machining time. Along the preparation process of the NC-program, two specific studies have been performed and are presented in this thesis. Although two distinct combinations of cutting data might provide the same MRR, the tool life and machining costs can be different. Therefore, selection of appropriate cutting parameters that best meet all these objectives is challenging. An algorithm for analysis and efficient selection of cutting data for maximal MRR, maximal tool utilization and minimal machining cost has been developed. This thesis also includes a theoretical study to estimate energy use, CO2-footprint and water consumption during manufacture of a workpiece, which can be invaluable for companies in their search for sustainability of their manufacturing processes.

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