Analysis and direct optimization of cutting tool utilization in CAM

Ana Esther Bonilla Hernández
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To my family
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October 2015
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October 2015
Populärvetenskaplig Sammanfattning

Nyckelord:

CAM programmering; Avverkning shastighet; Verktygslivslängd; Verktygsutnyttjande; Skärdata; Lean; Optimering; CIM; Integrering IT-verktyg; Tillverkning

Jakten på ökad produktivitet och kostnadsreduktion vid skärande bearbetning kan tolkas som en önskan att öka avverkningskapaciteten och maxera utnyttjandet av skärverktyget. CNC-processen är mycket komplicerad och påverkas av många olika begränsningar och parametrar, som sträcker sig från toleranser till be arbetbarhet. En väl genomförd förberedelseprocess skapa grunden för att lyckas uppnå få fel och kort bearbetningstid. Längs beredningsprocessen av NC-programmet har två olika studier genomförts, som presenteras i denna avhandling.


Den andra studien omfattar en utvärdering av hur skärverktyg används med avseende på avverkningshastighet och hur de utnyttjas. En algoritm för livslängdsstrategi användes för utvärdering av ett befintligt CNC-program. Utvärderingskriterier var "utnyttjad verktygslivslängd" och "återstående livslängd". Dessa användes för att utvärdera om verktygen har använts till det yttersta för förväntad livslängd, eller bidra till ett ackumulerat bortfall av tillgänglig verktygskapacitet.

Som ett resultat av de två studierna har en modell för analys och effektivt urval av skärdata för maximal avverkningskapacitet och maximalt verktygsutnyttjande utvecklats. Många tekniska hjälpmedel har införts under årens lopp för att förbättra effektiviteten vid CAM programmering. Den presenterade modellen förkortar tiden som ägnas åt att optimera valet av skärdata och de nödvändiga iterationerna som krävs vid programutveckling.
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The search for increased productivity and cost reduction in machining can be interpreted as a desire to increase the Material Removal Rate and maximize the cutting tool utilization. The CNC process is complex and involves numerous limitations and parameters; ranging from tolerances to machinability. A well-managed preparation process creates the foundations 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.

The first study examined the CAM programming preparation process from the Lean perspective. The investigation was carried out based on Lean principles and semi-structured interviews to CAM Programmers. In the search of reducing the development time of a project, several possible improvements are proposed, both as organizational improvements and as the improvement of the software by the generation of new features.

The second study includes an evaluation of how the cutting tools are used in terms of Material Removal Rate and tool utilization. An end-of-life strategy algorithm was applied for the evaluation of an existing CNC program. Utilized tool life and remaining tool life were used as criteria to evaluate if the tools were used to their limits of expected tool life, or contributing to an accumulated tool waste.

As a result of the previous studies, a model for the analysis and efficient selection of cutting data for maximal Material Removal Rate and maximal tool utilization has been developed and is presented here. Numerous technical aids have been introduced over the years in order to improve the CAM programming efficiency. The presented model shortens the time dedicated to the optimized cutting data selection and the needed iterations along the program development.
Abstract

Title: Analysis and direct optimization of cutting tool utilization in CAM

Keywords: CAM programming; Material Removal Rate; Tool life; Tool wear; Tool utilization; Cutting data; Lean; Optimization; CIM; Integration IT tools; Manufacturing

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IV. APPENDED PAPERS

Paper A. Streamlining the CAM programming process by Lean Principles within the aerospace industry


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

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

Presented at the 22nd CIRP conference on Life Cycle Engineering in Sydney, Australia, April 2015 – Authors: Ana Esther Bonilla Hernández, Tomas Beno, Jari Repo, Anders Wretland

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

Submitted for publication to CIRP Journal of Manufacturing Science and Technology – Authors: Ana Esther Bonilla Hernández, Tomas Beno, Jari Repo, Anders Wretland

Author’s contribution: Principal and corresponding author. Developed and analyzed the presented model. Wrote the main manuscript text.
Nomenclature

Variables:
- Depth of cut [mm]
- Taylor tool life equation constants
- Constant which represent the cutting speed for which the tool life is one minute
- Diameter of the work piece before machining operation [mm]
- Diameter of the work piece after machining operation [mm]
- Feed [mm/rev]
- Specific cutting force [N/mm²]
- Machined length of the work piece [mm]
- Spindle speed [rpm], Maximal spindle speed [rpm]
- Machine efficiency (in terms of power)
- Cutting power required [W]
- Maximal power provided by the machine [W]
- Specified MRR-level [cm³/min]
- Nose radius of the cutting tool [mm]
- Average surface roughness on machined surface [µm]
- Tool life [min]
- Machining time for the k:th operation [min]
- Effective cutting time [min]
- Volume of material removed [cm³]
- Flank wear [mm]
- Cutting speed [m/min]

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
- CNC Computer Numerical Control
- HRSA Heat resistant super alloy
- HSS High-speed steel
- MRR Material Removal Rate [cm³/min]
- NC Numerical Control
Nomenclature

Variables:
\( a_p \) Depth of cut [mm]
\( \alpha, \beta, \gamma, C_t \) Taylor tool life equation constants
\( C \) Constant which represent the cutting speed for which the tool life is one minute
\( D_0 \) Diameter of the work piece before machining operation [mm]
\( D_1 \) Diameter of the work piece after machining operation [mm]
\( f \) Feed [mm/rev]
\( k_c \) Specific cutting force [N/mm²]
\( L_z \) Machined length of the work piece [mm]
\( n, n_{max} \) Spindle speed [rpm], Maximal spindle speed [rpm]
\( \eta \) Machine efficiency (in terms of power)
\( P_c \) Cutting power required [W]
\( P_{\text{max}} \) Maximal power provided by the machine [W]
\( Q_i \) Specified MRR-level [cm³/min]
\( r \) Nose radius of the cutting tool [mm]
\( R_a \) Average surface roughness on machined surface [µm]
\( T \) Tool life [min]
\( t_k \) Machining time for the k:th operation [min]
\( t_m \) Effective cutting time [min]
\( V \) Volume of material removed [cm³]
\( V_B \) Flank wear [mm]
\( v_c \) Cutting speed [m/min]

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
CNC Computer Numerical Control
ETL Expected tool life [min]
HRSA Heat resistant super alloy
HSS High-speed steel
MRR Material Removal Rate [cm³/min]
NC Numerical Control
I. INTRODUCTORY CHAPTERS

1 Introduction

Nowadays, large amounts of cutting tools are not used to the full extent of their intended life. Therefore, cutting tools might be scrapped before reaching their full utilization. This implies that considerable amounts of not only materials but also energy are wasted daily.

In addition, the not fully utilized cutting tools also indicates that tool changes are planned more often than needed, thereby increasing the percentage of non-cutting cycle-time in the machine tools. These machines tools are expensive and should therefore be utilized as much as possible in order to keep the production profitable. But also in order not to further contribute to unnecessary use of scarce resources.

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 the cutting tools from a higher cutting speed or feed rate perspective. In many cases, the machining process is only slightly improved or even remains at a similar MRR. 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. However, assuming that the depth of cut in general remains unaltered when an insert is selected or changed, the two most prominent parameters remaining for process analysis and waste reduction are the cutting speed and the feed rate.

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 [1].

Every company that wants to be competitive in the global market shall strive to reduce the time to market for new products [2]. They shall also strive to satisfy every customer and their individual demands with customized products.
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Every company that wants to be competitive in the global market shall strive to reduce the time to market for new products [2]. They shall also strive to satisfy every customer and their individual demands with customized products.
Thereby the increase of variety and small volume production, which must still equally aimed for products of high quality and cost effective production [3]. 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 [4].

One 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 perseverant robustness.

Many companies look for ways to convert their tacit knowledge into models that can be stored, shared and reused in new projects [5]. The outcome sought in such strategies, is the possibility to re-use 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 [6].

The focus of this work is on companies with low product volumes that produce complex parts, such as aerospace companies. A large part of the 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 production processes. In modern CAM systems, there is still a lack of guidance for the CAM Programmer to define the best possible cutting data and points at the work piece where the tool shall be changed with regard to tool life and tool utilization.

The tools needed when machining hard-to-machine materials represent a significant percentage of the total cost [7]. The cutting tools used to machine difficult to machine materials such as Nickel-based super alloys exhibit high wear rates, thereby the high amount 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 environment in order to identify possible inefficiencies in today’s workflow that could be further improved. The outcome of this work will facilitate the development of new algorithms and knowledge, in order to make technology data more accessible in a CAM system and to support the CAM Programmer with optimized cutting data, with respect to tool wear during the CAM program development stage.

1.2 Limitations

The work presented here has several limitations. First, only one company was investigated for the study of the CAM programming process as representative of the aerospace industry. Second, the CNC program of one component was selected for evaluation of the cutting tool utilization in current production. Last, longitudinal turning was selected as the machining operation to investigate the cutting tool utilization and to develop the presented model for analysis and selection of cutting data.

1.3 Research questions

To be competitive, every company has the need to reduce waste and keep focus on the value adding activities [8]. To get an understanding of the processes and
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1.3 Research questions

To be competitive, every company has the need to reduce waste and keep focus on the value adding activities [8]. To get an understanding of the processes and
the efficiency in the utilization of the different resources available, the research questions studied in this thesis are presented in the following:

1. **How do the CAM Programmers conduct the CAM programming process?**
2. **What kind of inefficiencies exists in the CAM programming process from the Lean perspective?**
3. **How are the cutting tools used in production with respect to tool utilization?**

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 workflow can result in a more cost effective product development process and consequently more effective production. Thus, the last research question is formulated as:

4. **How can the cutting data selection be optimized during the tool path generation?**

### 1.4 Research approach

The research work has been divided into three main tasks:

In order to understand the CAM programming workflow and how the CAM Programmers are involved in the workflow, an investigation of the CAM programming process from the Lean perspective was performed based on Lean Principles and semi-structured interviews to 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.

In order to create a solid ground and to understand how the part geometry data at different stages of the CAM programming workflow is related to the cutting tool technology data, an existing CNC program for machining an advanced aero engine components of HRSA materials was analyzed with respect to Material Removal Rate and cutting tool utilization. Insights into the current situation in the CAM programming environment were gained through this case study.

A model for efficient selection of cutting data with focus on maximal MRR and tool utilization has been developed. This model or algorithm provides the structure for how to integrate advanced technology data in the CAM
programming workflow based on the part geometry data and cutting tool technology information.

A visual representation of the investigated areas is presented in Figure 1.

![Figure 1: Visual representation of the areas investigated](image)

1.5 **Thesis outline**

This thesis is outlined as follows:

Section I is dedicated to the introductory chapters (Chapters 2-3). A brief historical background and short description of CAM programming and Lean principles are presented. This section also presents the merger of tool life equation and MRR by superimposing them.

Section II is dedicated to the investigation chapters (Chapters 4-6). 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 workflow. Next, the findings of a second study with focus on how the cutting tools are used in production are presented. Finally, this section presents a developed model or algorithm for cutting data selection based on maximal MRR and tool utilization.

Section III is dedicated to the conclusive chapters (Chapters 7-9). An analysis of the findings is presented in this section, together with the conclusions, a short discussion and suggestions for further work.

Finally, Section IV includes all the appended papers.
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 [9].

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 [9]. 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 [9-12].

During the 18th century, the development of boring 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 which 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 [11]. 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 [13].

Further improvements in computational technology and computational speed helped the development of Computer-Aided Design, CAD, Computer-Aided
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Further improvements in computational technology and computational speed helped the development of Computer-Aided Design, CAD, Computer-Aided
Manufacturing, CAM and Computer-Aided Engineering, 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.

### 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” [9]. 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 [14].

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” [14].

New product requirements demand a greater complexity of the work pieces 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 work pieces 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 [14].

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” [10]. 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” [5]. Namely, PLM helps in the creation, recollection 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 [15].

In order to ensure the re-utilization of information and knowledge in future projects, recollection 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. As an example, 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 [10, 14].

The inputs to the CAM process are the CAD models. The CAM software combines information of the work piece 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 [16]. This flow includes the steps from the model design, CAD, as the start point. 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 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.

![Figure 2: CAM programming flow, extracted from [16]](image-url)
2.4.1 Status in CAM programming

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.

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 [17].

As a prediction from the author, knowledge from later stages of the development and manufacturing processes will be brought to earlier stages. Further system integration will enable the possibility to save that knowledge and re-use it to ease the decision process on an earlier stage of the product development.

2.5 Fundamentals of Lean

The concept of Lean started in Japan after the World War II within the automotive industry [18]. Lean is a way of working, a philosophy, a culture in which the whole company shall take part. According to the Japanese culture, the core of the production system is to eliminate waste or inefficiencies. The Lean principles [19, 20], are rooted in manufacturing but can yet be applied to other areas [21, 22]. The application of Lean generates both benefits and challenges [23, 24]. 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.

Every organization can be classified in terms of resource efficiency and flow efficiency, as presented in Figure 3 by the efficiency matrix [25]. The efficiency matrix is divided into four sections. The “Wasteland” section is where both
resources and flow are poorly utilized. An example of 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.

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. 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. 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”.

![Lean efficiency matrix](image)

Figure 3: Lean efficiency matrix, extracted from [25].

2.5.1 Lean considerations

The time to market is a key metric for any company. 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 [26].
The inclusion of “concurrent engineering” has a greater impact in every project. An early and right decision is always less costly. It is needed to keep in mind that what a company can do is limited. Every company must know where the competitors are, have a clear picture of how they will develop and grow as a company, and continue being profitable while reducing costs, innovating, improving features and quality [27].
Superimposing a tool life equation to 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 evaluate the efficiency in which the company is run. The selection of cutting speed, feed and depth of cut will determine the MRR value in which a cutting tool is used. The amount of time that a cutting tool can be used, namely tool life, is dependent on the same variables. Therefore, even if the combination of the variables will provide the same MRR, the tool life can be different, as represented in Figure 4.

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, namely to remove the unwanted material rapidly, it is important for every company to be able to have a metric such as the Material Removal Rate. MRR is the volume of material that is removed per minute and given as the product of the cutting speed, feed, and depth of cut,
3 Superimposing a tool life equation to MRR

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![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, namely to remove the unwanted material rapidly, it is important for every company to be able to have a metric such as the Material Removal Rate. MRR is the volume of material that is removed per minute and given as the product of the cutting speed, $v_c$, the feed, $f$ and the depth of cut, $a_p$:
In this work the depth of cut, \( a_p \), is considered to be constant, therefore MRR (1) 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

\[
\arg \max_{v_c f} MRR(v_c, f) = Q_t
\]

where \( Q_t \) 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 \( Q_t \). Each iso-MRR represented doubles the value of \( Q_t \) of the previous iso-MRR. Note that there are several combinations of \( \{v_c, f\} \) values that, for a constant depth of cut, will generate the same Material Removal Rate value. But a different combination of those parameters will result in different tool life.

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 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 \( Q_t = 640 \) [cm³/min] on the bold curve. Each iso-MRR represented doubles the value of the previous iso-MRR.
### 3.2 Influencing variables

The three main influencing variables in the cutting process are the cutting speed, the feed and the depth of cut, which constitutes the cutting data. Other influencing variables are the material to be machined; the application of cutting fluid and its pressure considered as coolant conditions; and the cutting tool including the tool material, the tool geometry and the nose radius.

Presented in Table 1 are the summary of how the three main variables might influence in a positive or negative way in the value of i.e. 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, 9, 28-36].

<table>
<thead>
<tr>
<th>Cut data:</th>
<th>Material Removal Rate</th>
<th>Spiral Cutting Length</th>
<th>Machining Time</th>
<th>Cutting Area</th>
<th>Tool:</th>
<th>Tool Wear</th>
<th>Tool Life</th>
<th>Others:</th>
<th>Cutting Forces</th>
<th>Cutting Power</th>
<th>Temperatures generated</th>
<th>Demands on surface:</th>
<th>Ra (Surface Roughness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed</td>
<td>↑</td>
<td>−</td>
<td>↓</td>
<td>−</td>
<td>↑</td>
<td>↓</td>
<td>−</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>−</td>
</tr>
<tr>
<td>Feed</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
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<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Depth of Cut</td>
<td>↑</td>
<td>−</td>
<td>−</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

### 3.3 The cutting process

The cutting process is the art of removing unwanted material in form of chips, from a shapeless block of raw material. Different cutting operations define how the material is removed. There are three main cutting operations or processes
such as turning, milling and drilling. The aim of the cutting process is to obtain
the final geometry of the work piece.

The cutting process is best described as a two dimensional cutting process. Therefore, a short description of the orthogonal cutting process, represented in Figure 6, is presented as follows.

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 create a primary shear zone in 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 work piece.

As represented 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 line perpendicular to the work material.
3.3.1 Longitudinal turning operation

The longitudinal turning, represented in Figure 7, was the operation selected during the case study. It is therefore presented here as an example of cutting process, including its formulas [9, 32, 37].

For this operation the depth of cut, $a_p$, can be defined as the difference between the work piece diameter before, $D_0$, and after, $D_1$, the machining operation, divided by two:

$$a_p = \frac{D_0 - D_1}{2} \quad (3)$$

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, $a_p$, and the feed, $f$:

$$A_c = a_p f \quad (4)$$

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

$$v_c = \pi D_0 n \quad (5)$$

The cutting power required, $P_c$, can be defined as the product of the specific cutting force, $k_c$, the feed, $f$, the depth of cut, $a_p$, and the cutting speed, $v_c$:
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, $ΔZ$, divided by the feed, $f$.

$$SCL = \frac{p}{f} = D_0\pi \frac{ΔZ}{f} (7)$$

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 as the same time can be define as the product of feed, $f$, and spindle speed, $n$:

$$t_m = \frac{L_Z}{v_f} = \frac{L_Z}{f \cdot n} (8)$$

The effective machining time, $t_m$, can also be calculated as the $SCL$ divided by cutting speed, $v_c$:

$$t_m = \frac{SCL}{v_c} (9)$$

The volume of material removed, $V$, can be calculated as the product of the feed, $f$, the depth of cut, $a_p$, the cutting speed, $v_c$, and the machining time, $t_m$:

$$V = f a_p v_c \cdot t_m (10)$$

The average surface roughness, $R_a$, can be calculated as a function of the nose radius of the cutting tool, $r$, and the feed, $f$:

$$R_a = \frac{f^2}{32r} (11)$$

### 3.4 Work piece material

The work piece 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 in the tough working conditions of such machines. 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. Nickel-based alloys are widely used in such applications, and are therefore selected as the material for this work. The
characteristics of this material are a 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 [38].

Every material has a machinability index that is calculated in comparison with the steel AISI 1212, to which a machinability indicator of 100% has been ordered. HRSA have a machinability index that range between 10% and 24%, which is significantly lower with respect to steel [32].

### 3.5 Cutting tool materials

There are several materials used for cutting tools, mainly developed during the 20th century. Those materials range from steels to cemented carbides, ceramics, diamonds and boron nitride. The selection of the cutting tool material together with the cutting data leads ultimately to a successful and robust cutting operation [39].

The desired properties from cutting tool materials are hardness, wear resistance, toughness, deformation resistance, hot hardness, heat resistance, chemical resistance, tendency not to stick to the work piece material, producibility and cost [32].

For this work, as has already been mentioned in Chapter 3.4, the work piece materials are HRSA which are considered difficult-to-machine. The selection of the cutting tool materials depends on the work piece material. In the case of HRSA, the cutting tool materials recommended are High Speed Steel, Cemented Carbides and Ceramics [39]. The use of High Speed Steel has decreased in benefit of both Cemented Carbides and Ceramics. These cutting tool materials present the desired properties to machine HRSA which are necessary to reduce too rapid tool wear.

### 3.6 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. The most influential parameters are the cutting tool material; the cutting tool geometry; the cutting conditions including the cutting data, the type of cutting operation and the application of cutting fluids; and the work piece material [39].
These parameters will affect the contact stresses between the work piece and the cutting tool, and thus the prevailing temperature in the cutting zone. Therefore the tool wear is dependent on different factors such as loads, temperatures and chemical reactions. Every physical basic 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 will result in crater wear; adhesion wear mechanism will result in built-up-edge (BUE); and fatigue will result in plastic deformation or cracks.

The tool wear can emerge either as premature or gradual failure. Elevated cutting forces can develop a premature brittle failure of the cutting tool as well as elevated temperatures generated by the cutting process can develop a premature thermal failure due to thermal effects, thus the use of cutting fluids. Gradual failure of the cutting tool allows the use of the cutting tool longer time; therefore this is the preferred failure mode of the tool.

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 final failure, as represented in Figure 8 [40].

![Figure 8: Tool wear as a function of cutting time and flank wear [40]](image)

### 3.6.1 Flank wear

Flank wear occurs on the clearance face of the cutting tool, which is the one in contact with the work piece material during the cutting operation. Flank wear, as represented in Figure 9, 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 \( (V_B) \) [39].

![Figure 9: (a) Representation of the cutting tool with indication of the view on the left image. (b) Flank wear representation, extracted from [9] (3.6.1 Flank wear)]

3.6.2 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 10, is predominant at high cutting speeds. Diffusion wear is the dominant mechanism as consequence of the chemical reaction between the cutting tool and the work piece materials due to the elevated temperatures. Crater wear can weak the cutting edge to the point of fracture [39].

![Figure 10: (a) Representation of the cutting tool with indication of the view on the left image. (b) Crater and Nose radius wear representation, extracted from [9] (3.6.2 Crater wear)]
3.7 Tool life

Tool life can be described as the amount of time that a tool can be used until the flank wear has reached the tool life criteria [28], as shown in Figure 11. The diagram shows the influence of the cutting speed, $v_c$, on the cutting tool life, $T$, where a lower value of cutting speed will wear the cutting tool in a different rate allowing to increase the amount of time that can be used for cutting and therefore allowing the increase of tool life.

![Figure 11: Relationship between the flank wear criteria ($V_b$) 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 (9), in the case of longitudinal turning operation, tool life can be described as the amount of length (SCL) that a tool can be used until the flank wear has reached the tool life criteria, which is commonly used [41, 42] and could be represented similarly to Figure 11.

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, $V_B$, if the flank is regularly worn; or 0,6 mm of flank wear, $V_B$, if the flank is irregularly worn, scratched or chipped [40]. From the author’s experience, the same wear criteria are also commonly used for cemented carbide tools in industrial applications.

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

Over the last century, several researchers have developed models to describe how the cutting tools wear progress over time. Some of the most commonly used tool wear rate models are: Taylor’s tool life equation [28]; Takeyama and Murata’s wear model [43]; Usui’s wear model [44]; Archard’s wear model [45] and Colding’s tool life equation [1].

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

Other CAM simulation studies [46] consider the cutting data (cutting speed, feed and depth of cut), together with part geometry, spindle speed and type of tool the most influencing variables in the machining process. Therefore the selection of the Taylor’s tool life equation as tool wear model for this work.

\[ v_c T^\alpha = C \]  

(12)

Where \( T \) is the tool life, \( v_c \) is the cutting speed, \( \alpha \) and \( C \) are constants empirically determined constants. \( \alpha \) can be represented as the slope of the tool life curve when represented in a log-log scale, as shown in Figure 12. \( C \) represents the cutting speed for which the tool life is one minute [28].

The original Taylor tool life equation (12) 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 are also significant. Therefore the development of the extended Taylor’s tool life equation:

\[ v_c T^a f^b a_p^c = C_t \]  

(13)

Where \( T \) is the tool life, \( v_c \) is the cutting speed, \( f \) is the feed, \( a_p \) is the depth of cut, and \( a, b, \gamma \) and \( C_t \) are constants empirically determined for each specific combination of cutting operation-work material-cutting tool used [31].

3.8.1 Calculation of Taylor Tool life equation constants

The Taylor tool life equation constants are related to the contribution to the tool wear from each one of the cutting parameters. A large value indicates a strong influence to the tool wear with decreasing tool life as a consequence.

As shown by previous research [47], it is possible to construct a system of four equations with four different “working points or data” recollected and convert these equations from non-linear to linear, obtaining a system of four linear equations. Therefore, using four different empirical catalogue data points provided by the tool supplier, it is possible to obtain the four constants \( a, b, \gamma \) and \( C_t \).

For this work, four cutting data points were selected from [48] for a rough turning operation on a component made from HRSA with a ceramic cutting tool and 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 which are 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 [30, 31, 49] are $\alpha$ within the range of 0.5 to 0.7; $\beta$ shall be smaller than 1 because the influence of feed is less significant than the influence of the cutting speed; and $\gamma$ shall be smaller than $\beta$ 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.

### 3.9 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 $\{v_c, f, a_p\}$. Therefore, the Taylor’s tool life equation will become a time varying function of the time varying cutting data, as shown in Figure 13.

![Figure 13: Piece-wise constant Taylor's tool life for three subsequent machining operations.](image)

A cutting tool supplier often provides a recommended set of cutting data. The recommended cutting data may however not be the most suitable for a specific machining operation, depending 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 (13) is used to estimate the expected tool life, \( ETL \), by

\[
ETL(v_c, f, a_p) = T(v_c, f, a_p) = \left( \frac{C_t}{v_c f^p a_p} \right)^{\frac{1}{a}} \tag{14}
\]

The general expression for utilized tool life, \( UTL \), 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, cutting speed, \( v_c \), feed, \( f \), and depth of cut, \( a_p \), may be altered. The tool utilization is given with the effective machining time \( t_m \) and \( N \) machining operations as:

\[
UTL\% = \frac{t_m}{ETL} \times 100\% = \sum_{k=1}^{N} \frac{t_k}{ETL(v_{c,k}, f_k, a_{p,k})} \times 100\% \tag{15}
\]

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

\[
t_m = \sum_{k=1}^{N} t_k \tag{16}
\]

The remaining tool life, \( RTL \), is obtained by subtracting the total machining time from the expected tool life:

\[
RTL(v_c, f, a_p) = ETL(v_c, f, a_p) - t_m \tag{17}
\]

Remaining tool life, \( RTL \), can also be obtained by subtracting \( UTL\% \) from the total as:

\[
RTL\% = 100 - UTL\% \tag{18}
\]

This implies, that in order to optimize tool utilization in practice 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.
II. INVESTIGATION CHAPTERS

4 Study of the CAM programming workflow 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 perform their work, how they are organized and how they relate to the different projects.

As an alternative to interviews, observation was considered, but was rejected due to time consumption and the high risk for reflexivity (influence between interviewer and interviewees). Surveys were also considered to be conducted, but 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. Different views from the interviewees corroborated that the interviews were not biased in any “conspiratorial” way between the interviewees, or by reflexivity [50]. The interviewees involved in this paper could provide a clear view of the situation; provide explanations as well as personal views.

The study of the CAM programming process is centred in one company within the aerospace industry. To investigate the possible inefficiencies within the CAM programming process and how the available resources are used, semistructured interviews with one open question were the selected method. Like that, the interviewees could neither be influenced nor guided in their answers. The interviewed were asked an open question to describe the CAM programming process and freely discuss the subject. By using an open question, the CAM Programmers got the freedom to explain how they really work and how they experience the CAM programming process.

Interviews were used to confirm that the work flow used is similar to the one presented in Figure 2, but more details were needed for the Lean study. The summary of the interviews is appended in Paper A.
4.1 Detailed description of the CAM programming flow

A detailed CAM programming flow is proposed, which is generated guided by the semi-structured interviews with CAM experts. Therefore, the flow presented in Figures 14-19 is specific for the studied aerospace company. The work flow is divided in three main stages, represented in Figure 14. The first stage, corresponding to the process planning is represented in detail in Figure 15. The secondary flow for tool selection is presented in Figure 16 and the secondary flow for clamping system selection is presented in Figure 17. The second stage, represented in Figure 18, correspond to the definition steps. Finally, the third stage, corresponding to the CAM programming is represented in Figure 19.

Note that in Figures 14-19, a grey scale has been used to differentiate the steps that belongs to the different stages of design, process planning and manufacturing; similarly to what was presented in Figure 2. The numbering in the figures is explained in more detail below.

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.

![Figure 14: Three main stages of the CAM programming flow from CAD model design to the generation of NC program.](image)

The initial input of the CAM programming flow is the CAD model or design (Figure 15).
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. The blank selection is an important step because it will determine the amount of material that shall be removed during the machining operations. Knowing that a high percentage of material is to be removed, the blank selection is done as “near net
A detailed CAM programming flow is proposed, which is generated guided by the semi-structured interviews with CAM experts. Therefore, the flow presented in Figures 14-19 is specific for the studied aerospace company. The workflow is divided into three main stages, represented in Figure 14. The first stage, corresponding to the process planning, is represented in detail in Figure 15. The secondary flow for tool selection is presented in Figure 16 and the secondary flow for clamping system selection is presented in Figure 17. The second stage, represented in Figure 18, corresponds to the definition steps. Finally, the third stage, corresponding to the CAM programming, is represented in Figure 19.

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.

Figure 14: Three main stages of the CAM programming flow from CAD model design to the generation of NC program.

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. The blank selection is an important step because it will determine the amount of material that shall be removed during the machining operations. Knowing that a high percentage of material is to be removed, the blank selection is done as “near net shape” as possible. This step is carried out in collaboration with the Material Engineer.
3. The processes to be used are selected, and this selection is also an outcome from the flow. This is an important step because the process selection determines the productivity, which any company shall prioritize. The selected processes are divided into groups corresponding to the main processes, such as turning, milling, and drilling. This step is carried out in collaboration with the Process Engineer.

Figure 15: Detailed CAM programming flow Stage 1: Process Planning Stage.
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. In the aerospace industry, production 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. Once the machines are selected, the machine models will be an outcome from the flow. This step is carried out in collaboration with the Process Engineer and the Production Planner.

5. Two secondary flows shall be started in parallel at this point because both of them normally take several weeks. They are considered as secondary flows because the CAM Programmer only supervises them, but the interaction with both the Tool Supplier and the Clamping System Designer is essential.
   a. One of the secondary flows is the tool selection, Figure 16, 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. Assistance is provided by the different Tool Suppliers during the tool selection. In the case that there is a standard tool that can be used, that tool is selected. In the case that there is no suitable standard tool available, a new tool needs to be defined. The supplier develops the tool and tests it, and the new tool is selected. Once the tool is selected, either standard or not, a purchase order is issued and the tool model is obtained as an outcome.

   The delivery of tools and tool holders may take several weeks. The selection of an “inappropriate” tool can lead to the need of a new tool including its definition and development. Delays on the cutting tool and tool holder deliveries might cause unwanted delay in a project with a fixed schedule.
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b. The other secondary flow is the clamping system selection, Figure 17, 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, also fabricated. This is particularly important for the machining of thin-walled components as is frequently the case in the aerospace industry. The clamping system has an impact on the stability of the cutting process and therefore affects the final dimensions and tolerances of the component. Once the clamping system is approved, the clamping model is obtained as outcome and its fabrication starts.
6. The different models for the machines, clamping system, cutting tools, cutting tool holders and blank shall first be defined in another software (definition software). This is done by the CAM Programmer and it is required before importing those models together with the CAD model in the CAM program, as represented in Figure 18. At this point, a second interpretation of the models or drawings is performed.

7. Information from the processes selected and the process definitions shall be taken into the CAM system for each main process (turning, milling and drilling).

8. The selected operational machine model is imported and defined in the CAM system.

9. The blank and the work piece models are imported in the CAM system.

10. The selected clamping model is imported and defined in the CAM system.

11. The models of all the selected tools are included in the CAM system.
12. 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. This step might take several iterations, as represented in Figure 19.

13. Machining parameters shall 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. From there, 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 this step might also, like the previous, 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 19.

15. Once the tool path is generated, the CAM Programmer starts a series of simulation and verification operations that go from simple to more complex ones. While increasing the complexity of those simulations and verifications, the time needed to perform them will also rise. If an issue is encountered at this step, it is typically corrected by reversing to the operation definition and the machining parameters selection steps. On the other hand, if no issue is encountered, the CAM Programmer proceeds with the next step.

Figure 19: Detailed CAM programming flow Stage 3: CAM programming Stage.
16. The CAM Programmer orders the operations in the production sequence.
17. The CAM Programmer creates a measuring program, used for quality assurance during production.
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 with this is to ensure that all the tests, as near as reality as possible, have been performed before a 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. 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.

4.2 Analysis of the CAM workflow from the Lean perspective

In order to identify the key steps along the CAM programming workflow, an evaluation has been performed per step with regard to three different criteria, presented in Table 4. All criteria have been evaluated in 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. The first criterion is the relevance or importance of each step, mainly depending on the consequences that a bad decision at that step can generate. Further, the second criterion is the time needed to perform each step. And finally, the third criterion is the skills or experience required by the CAM Programmer to be able to perform each step.

Note that in Table 4, a grey scale has been used to differentiate the steps that belongs to the different stages of design, process planning and manufacturing; similarly to what was presented in Figure 2.
Table 4: Analysis of the CAM programming flow by relevance, time needed and experience required per step.

<table>
<thead>
<tr>
<th>#</th>
<th>Work flow step</th>
<th>Relevance/Importance</th>
<th>Time needed</th>
<th>Skills/Experience required</th>
<th>Key step</th>
</tr>
</thead>
<tbody>
<tr>
<td>In</td>
<td>Initial CAD model/design</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Drawing interpretation</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Blank selection</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Process selection</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Machine selection</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>5a</td>
<td>Tool selection</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>5b</td>
<td>Clamping system selection</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Model/drawing interpretation</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Process definition into CAM system for each main process</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>Machine definition into CAM system</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Blank/work piece definition into CAM system</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>Clamping definition into CAM system</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td>Tool selection into CAM system</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td>Operation definition</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
<td>Machining parameters selection</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>Tool path generation</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>15</td>
<td>Simulation and verification</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>16</td>
<td>Order operations</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>17</td>
<td>Measuring program</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td>Post-processing</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
</tr>
<tr>
<td>19</td>
<td>Simulation and verification in second software</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td>Real test</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Out</td>
<td>Freeze program</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>Component inspection</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>No</td>
</tr>
</tbody>
</table>
The key steps can be divided into two groups. One group contains all the key steps during the process planning, which include the process selection, the machine selection, the tool selection and the clamping system selection. The selections in these steps will set up for instance, the machine park utilization, the productivity, and the basis for the machining operations and the dimensional accuracy in the component.

The second group contains all the key steps during the programming for machining, which include the operation definition, the machining parameters selection, the tool path generation and the simulation and verification. These steps require a high 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 the high relevance, the high amount of time required and the high skills required of the CAM Programmer.

### 4.2.1 Involvement of the stakeholders

Along the CAM programming flow, the CAM Programmer is held responsible, (R (Table 5)), of the main process, although several stakeholders from different departments are involved in the process, (X (Table 5)). Table 5 present the involvement of the different stakeholders in the CAM programming work flow.

As mentioned, the input of the flow is the CAD model or design, for which the responsibility belongs to the CAD designer. The Product Designer and the Project Leader are also involved in this step.

During the process planning, a rough estimation of the process is done thanks to the experience of the CAM Programmer and the involvement of other stakeholders. The different processes needed are selected, which will set up the basis for productivity, thus the high relevance. In order to select the appropriate processes high experience is required, thus the involvement of the Process Engineer during this step. The machines to be used shall also be selected, which will set up the way the company uses its machine park and thereby the high relevance. To assure a uniform working load among all the machines, high skills are required and thereby the involvement of both the Process Engineer and the Production Planner during the step. Tool selection and clamping system selection are both time consuming. Both steps influence the machining operations and the dimensional accuracy of the component, thus the high importance and high skills required.
Table 5: Involvement of the different stakeholders in the CAM programming flow

<table>
<thead>
<tr>
<th>#</th>
<th>Work flow step</th>
<th>CAD Designer</th>
<th>CAM Programmer</th>
<th>Fixture Designer</th>
<th>Fixture Fabrication</th>
<th>Inspector</th>
<th>Material Expert</th>
<th>Process Expert</th>
<th>Product Designer</th>
<th>Production Operator</th>
<th>Production Planner</th>
<th>Project Leader</th>
<th>Purchasing</th>
<th>Tool Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>In</td>
<td>Initial CAD model/design</td>
<td>R</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>1</td>
<td>Drawing interpretation</td>
<td>X</td>
<td>R</td>
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<td>2</td>
<td>Blank selection</td>
<td>R</td>
<td>R</td>
<td>X</td>
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<td>Process selection</td>
<td>R</td>
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<td>4</td>
<td>Machine selection</td>
<td>R</td>
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<td>5a</td>
<td>Tool selection</td>
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<td>5b</td>
<td>Clamping system selection</td>
<td>X</td>
<td>R</td>
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<td>Model/drawing interpretation</td>
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<td>Process definition into CAM system for each main process</td>
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<td>Machine definition into CAM system</td>
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<td>Blank/work piece definition into CAM system</td>
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<td>Clamping definition into CAM system</td>
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<td>Tool selection into CAM system</td>
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<tr>
<td>12</td>
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<tr>
<td>16</td>
<td>Order operations</td>
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<tr>
<td>17</td>
<td>Measuring program</td>
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<tr>
<td>18</td>
<td>Post-processing</td>
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<tr>
<td>20</td>
<td>Real test</td>
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Steps 1 through 5 are the ones corresponding to the process planning. The CAM Programmer is responsible for the steps which belong to the main flow; except during the blank selection where the CAM Programmer share responsibility with the Material Expert. Other stakeholders collaborating in these steps are the CAD Designer, the Process Expert, the Product Designer, the Production Planner, the Project Leader and Purchasing.

Typically, new tools shall be developed, therefore the Tool Supplier is held responsible for the tool selection step. The Fixture Designer is held responsible for the clamping system selection step, where the person responsible for the fabrication of the fixture is also involved.

Steps 6 through 21 correspond to the definition and manufacturing of the component. The CAM Programmer is held responsible for these steps where all the required manufacturing operations are developed, simulated, verified and tested. Other stakeholders involved are the Tool Supplier which provide the initial cutting data; the Production Operator; the Inspector and the Project Leader.

4.3 Findings

The work flow and the Lean considerations are discussed in more detail in the appended Paper A. A summary of the discussion is presented in this section.

The work flow simulates a production line and evaluate how the different “operators”, in this case the CAM Programmer, works along the flow. Each step represented in Figures 14-19 can be seen as a “station” within a production line, therefore the CAM Programming workflow is detailed enough to perform an analysis from the Lean perspective. The objective is to create a product, which in our case is a NC program describing a tool path. The mentioned tool path is simulated, verified and tested several times until it reaches a component inspection in production.

During the first stage of the CAM programming, the CAM Programmer makes a rough estimation of the processes, the cutting data and the machines needed. To perform these steps considerable experience is needed. The blank selection determines the amount of material to be removed, therefore the importance to involve the CAM Programmer in the project from the beginning to ensure this to be a minimum. CAM Programmers shall also have knowledge about costs, in order to be able to choose the best and least expensive from available options.
These may include the relative or approximate costs of processes, tooling, raw material, clamping systems, etc. Both secondary flows, cutting tool and clamping system selection, may take several weeks of time. Therefore an inappropriate selection during these flows may result in a delay in the project. These steps are considered essential for the project time planning.

Specific for the aerospace industry there is, for instance, the use of one additional definition software. This system is used both as a link between all the different programs used within the company and for traceability purposes, which is essential in an area where the product life might last for many decades.

Also specific for the aerospace industry is the use of a second software for simulation and verification. This software is used to simulate and verify the CL-file and detect potential issues that otherwise might occur in the production. The core function for this software is the provision of simulation and verification as close to reality as possible. Knowing the costs of both the materials, the parts produced and the equipment needed, it is a requirement to perform a test as close to reality as possible. Therefore the use of this second software cannot be discarded within the aerospace industry.

The set-up of the real test can also generate errors; therefore the need of a real test until a first article inspection has been performed.

### 4.3.1 Company specific organization

Looking into how the CAM Programmers are organized in the interviewed company, each CAM Programmer performs the whole process. Looking back into the efficiency matrix from [25] in Figure 3, it can be seen that the resources, or in this case the CAM Programmers are used efficiently but they each represent an “Efficient island”.

Aiming to reach the “Perfect state” shown in Figure 3, there is a need to increase the flow efficiency. In order to do that, the new path to be followed shall increase the flow efficiency, even at the price of decreased resource efficiency, therefore creating an “Efficient ocean”. To achieve this, it is needed to free some capacity of the resources to be able to increase the flow efficiency. Once an “Efficient ocean” is created, the efficient use of the resources can be increased again reaching the “Perfect state”. This new path is represented in Figure 20.
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The current organization of the CAM Programmers could be represented by a “short and fat” layout [51], represented in Figure 21. This layout has advantages such as flexibility, robustness and non-monotonous work.

In a “long and thin” layout [51], as presented in Figure 22, it will take too much time for each CAM Programmer to interpret what has been done until that step and be able to work with it due to the complexity of the parts.

Therefore a “mix” layout could be a good solution in the path towards the “Perfect state”. Move in the efficiency matrix from “Efficient islands”, through
“Efficient ocean”, towards the “Perfect state”. Two different organizational proposals are presented as follows.

4.3.1.1 First organizational proposal
The first organizational proposal, as presented in Figure 23, aims to allocate the more experienced people in the key areas and the less experienced people in the non-key areas. First, an expert group shall work during the planning process stage (steps 1-5 from Figure 15), where more contacts within the project and other departments are needed. A dedicated person is proposed to work with the mentioned definition software (steps 6-11 from Figure 18). The CAM Programmer will continue the workflow until the program is frozen and ready for production (steps 12-21 from Figure 19). This first organizational proposal allocates the CAM Programmers based on machining methods, as represented in Figure 23. By this, the CAM Programmers’ organization continues to be based on the different machining methods such as turning, milling or drilling.

![Figure 23: First organizational proposal as “mix” layout](image)

4.3.1.2 Second organizational proposal
Up to now, the CAM Programmers’ organization has been based with the main focus in the different machining methods. From the influence of 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.

The second organizational proposal, as presented in Figure 24, 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.
4.3.1.3 Comparison of the organizational proposals

The main benefit from both organizational proposals is the possibility to streamline the CAM programming process by improving the work flow efficiency.

An extra benefit from the second organizational proposal is that the use of platforms might guarantee that the knowledge gained during one project will be re-used, at least, in other projects within the same platform.

Both organizational proposals will split the group of CAM Programmers and allocate the most experienced people to an expert group and a dedicated person to work with the definition software. Note that by doing these changes; the communication between all the programmers will become crucial and this strategy can lead to the creation of a separation between the experienced and non-experienced CAM Programmers. As long term goal, all the CAM Programmers should be trained in all the steps of the process, thereby giving even more flexibility to the organization.
Analysis of tool utilization

A cutting tool supplier often provides a recommended set of cutting data. Normally, for a rough operation, the used values will be the highest recommended by the tool supplier and for a specific cutting operation - work piece material - cutting tool combination. The recommended cutting data may however not be the most suitable for a specific machining operation, depending 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, expected tool life and utilized tool life must also be taken into account. By having access to this, 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 MRR.

5.1 Investigation of the CNC program

The CNC programs provide information about the three-dimensional movement of the cutting tool tip. For turning, this can be simplified to a two-dimensional plane (X, Z). 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.

The CNC program selected for the study was a commonly round shape work piece where a high percentage of material, in this case HRSA, shall be removed by cutting operations. In the selected CNC program, several hundreds of cutting tools were used and among them, there was a standard cutting tool which was used in 35 occasions that eventually was chosen and scrutinized.

The cutting tool selected was a ceramic insert (RCGX 120700 SIA6060) which is commonly used to cut HRSA materials. This type of cutting tool is used due to its strength at high temperatures, high wear resistance, good oxidation resistance, excellent thermal shock resistance and heat resistance.
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The cutting tool selected was a ceramic insert (RCGX 120700 SIA6060) [48] which is commonly used to cut HRSA materials. This type of cutting tool is used due to its strength at high temperatures, high wear resistance, good oxidation resistance, excellent thermal shock resistance and heat resistance.
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.

After a first view of the CNC program, the majority of the movements or operations were linear interpolation (G01). Therefore as a first simplification, all the movements or operations (G01: linear; G02: circular, clockwise; G03: circular, counter clockwise interpolation) were considered to be linearly interpolated, as shown in Figure 25.

Each insert is used during a sequence of machining operations. By extracting the data provided by the CNC program, row by row, it is possible to split the operations into steps, which from now onward will be referred to as single operations, simplifying the calculations.

Thereby, the initial and final point of each single operation was extracted from the CNC program together with the cutting speed and feed used.

The spiral cutting length, SCL, was calculated, as a simplification, by using Equation (7). SCL was calculated as the product of the perimeter of the circumference described by the tool using the average value of X as diameter, and the movement in Z divided by the feed, Figure 25.

Once the SCL is known, it is possible to calculate the machining time, \( t_m \), for each single operation, with Equation (9), as the SCL divided by cutting speed.
Tool life was calculated with the extended Taylor's tool life equation, Equation (13), for each single operation. Similarly, the MRR and the chip volume removed, \( V \), were calculated with Equations (1) and (10) respectively for each single operation.

Knowing the tool life and the machining time for each single operation, it is possible to calculate the utilized tool life, \( UTL \), of each cutting tool as the sum of all the single operations in which the insert is used, Equation (15). Similarly, the remaining tool life, \( RTL \), can be calculated with Equation (18).

### 5.2 Findings

Every insert analyzed, was used with different feed rates, varying from single operation to single operation. Therefore, the inserts were used with 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 26.

In order to investigate how these unique combinations of cutting parameters were used, they were calculated as the percentage combining all the single operations for the 35 inserts investigated, represented in Figure 26. The inserts were mainly used above the MRR of the reference combination [48].
The utilized tool life for each insert investigated is represented in Figure 27, with \( UTL \)-values varying from 2% up to 104%.

The remaining tool life for each of the inserts studied is represented in Figure 28, with \( RTL \)-values ranging from -4% up to 98%.
5.3 Reasoning of the findings

The study showed that for this particular insert, the aimed MRR values were not the same as the reference values selected from the tool supplier recommendations. In this case, a rather conservative value of cutting speed was used and the feed varied between values from 0,15 up to 0,5 mm. Giving a total of six unique combinations of cutting data used with the inserts.

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 insert was used in a higher MRR level than the reference value in approximately 75% of the machining time, Figure 26. This 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. For a better visualization of the UTL chart in Figure 27, the inserts has been reordered from smallest to largest values and are presented in Figure 29. From this figures, it is possible to deduct that 40% of the inserts are used below 40% of their expected tool life. Further, 80% of the inserts are used below 75% of their expected tool life. This gives that only 20% of the inserts are used above 75% of their expected tool life.

![UTL (%) Chart](image)

**Figure 29:** Utilized tool life (UTL) for each studied cutting insert reordered from smallest to largest values.
For a better visualization, the $RTL$ chart in Figure 28, has been reordered from largest to smallest values and are presented in Figure 30. This provide evidence that around 50% of the accumulated tool life, for the 35 inserts studied, are not used and therefore wasted. These tools are regarded as an unnecessary addition to the total waste.

![RTL chart](image)

**Figure 30: Remaining tool life ($RTL$) for each studied cutting insert reordered from largest to smallest values.**

If this kind of data can be accessed while programming, 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. This measure might not be enough to correct the 50% of the tool life wasted, as the $RTL$ chart shows, Figures 28 and 30, but it is expected that significant improvements can be achieved.

There are also two exceptions, two inserts that has been used passed their expected tool life. The use of inserts above its expected tool life can lead to e.g. geometrical problems in the work piece. Knowing the tight tolerances used in the aerospace industry, this can lead to even greater material waste if the work piece must be scrapped. Therefore the use of the cutting tools above their expected tool life must be avoided.

It should also be added that only one type of the used inserts was studied, therefore the study conducted represents only a small part of the total
machining process. By the application of this same study to the whole component, it might be possible to achieve an even greater utilization of the cutting tools and reduction of the total machining time.
Integrated optimization algorithm for cutting data selection

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 to the total material volume that will be removed in the current working material during the service life of the cutting tool.

There are several cutting processes used to remove material from a workpiece in order to obtain the desired geometry. The cutting data values will vary depending if the selected operation is a rough or a finishing operation. An integrated optimization algorithm 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 the MRR and tool utilization.

6.1 Optimization of the parameters

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 three main variables is requested: the depth of cut, the feed and the cutting speed. The time required by the CAM Programmer to obtain optimal values can take several iterations. Therefore the use of an integrated optimization algorithm for cutting data selection can help the CAM Programmer to reduce the development time of the NC-program.

The optimization can be done with respect to different criteria such as maximizing production rate [52-54], minimizing cost [55], maximizing Material Removal Rate [56], or maximizing tool life [57]. In other words, to maximize the amount of parts machined per hour, minimize the total production cost of a...
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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 [58].

In industrial operations, where a high percentage of raw material needs to be removed and the machining time shall be kept to the minimum, MRR is an extensively used variable. As presented in Equation (1), MRR is a function of feed, \( f \), depth of cut, \( a_p \) and cutting speed, \( v_c \). The depth of cut is commonly defined to be constant for a certain situation.

Within the aerospace industry, due to the tight tolerances, a typical constraint is that the cutting tool must be changed at specific points in order to not disrupt the surface finish of the work piece. Therefore the cutting data must also 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.

It is important to find the balance between the two criteria of Material Removal Rate and tool utilization. In case of reducing MRR it might be possible to extend the tool life until the operation is finished avoiding for example a tool change. 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 31.

![Figure 31: Balance between MRR and tool utilization](image-url)
6.2 Description of the integrated algorithm

The algorithm integrates the iso-MRR curves, tool wear, tool life, tool utilization and constraints to obtain the best possible combination of cutting data assuring the maximization of MRR and tool utilization. This algorithm or model is also presented in the appended Paper C.

As input data for the model, the geometrical and material data from the work piece and the cutting tool are required. Depth of cut and aimed MRR are also required, as represented in Figure 32. The algorithm also requires some input of limitation data for calculation of the machining time, Equations (8-9), the iso-MRR curves, Equation (1) and the Taylor tool life equation constants, Equation (13).

The chosen cutting tool sets limitations to the feed and the cutting speed for a certain work piece material. The feed value has an upper limitation related to the maximal mechanical load that can be applied on the tool. Similarly, the cutting speed value has an upper limitation related to the maximal thermal load that the tool can withstand. Figure 5 shows an example of the initial cutting data work frame in terms of feed and cutting speed for a certain depth of cut, \(a_p\) and cutting tool.

As constraints for the algorithm, the maximal spindle speed, \(n_{max}\), that the cutting machine can provide, which will further constrain the cutting speed, \(v_c\), must be considered. The maximal power provided by the machine, \(P_{max}\), and the machine efficiency, \(\eta\), will provide a constraint on the power required during the cutting, \(P_c\), Equation (6). 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.

\[
P_c = \frac{f a_p k_c v_c}{60} \leq \eta P_{max} \quad (19)
\]

Another constraint is the expected average surface roughness, \(R_a\), after the cutting operation, Equation (11), which will constrain the feed. To assure the surface integrity, using the nose radius of the cutting tool, \(r\), and the expected \(R_a\), the algorithm calculates the maximal value for the feed as in:

\[
R_a = \frac{f^2}{32r} \Leftrightarrow f_{max} = \sqrt{\frac{32}{r} R_a} \quad (20)
\]

The algorithm starts calculating the iso-MRR curves for all the possible combinations of \(\{v_c, f\}\), excluding the ones with MRR lower than the aimed MRR. The algorithm includes the cutting power constraint, Equation (19), as an
upper limitation for MRR. The algorithm continues calculating $t_m$ including $n_{\text{max}}$ that will constrain the maximum $v_c$, Equations (8-9). The algorithm includes the nose radius of the cutting tool, $r$, and the expected $R_a$, that will constrain the maximum feed, Equation (20).

The algorithm calculates the expected tool life, $ETL$, the utilized tool life, $UTL$, and the remaining tool life, $RTL$ as previously described in Equations (14), (15) and (18) respectively. The last constraint of the algorithm is obviously that the $RTL$ is equal or greater than zero. Meaning that the machining time in which we use the cutting tool is lower or equal to its $ETL$.
The algorithm generates a valid combination area in which all the requirements and constraints are fulfilled including \( ETL, UTL \) and \( RTL \), and from where the \( \{v_c, f\} \) combination can be selected, as shown in Figure 33.

The valid combination area can be further reduced from the initial cutting data work frame presented in Figure 5 by taking into account all the aforementioned constraints as represented in Figure 33.

The initial or first cutting data combination taken is normally the one provided by the tool supplier. To optimize the cutting data, the algorithm generates a grid of valid points around that initial combination and moves along the grid selecting the one that provide greater MRR and tool utilization. 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 33 represents an example of the path of iterations from the first cutting data combination to the optimal cutting data combination.

After all the necessary calculations, the algorithm extracts the output data as the optimal cutting data combination \( \{v_c, f\}, ETL, UTL \) and \( RTL \).

Figure 33: 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.
6.3 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 of 200 [mm] and a length of 350 [mm].

The aimed MRR is 50 [cm³/min] and the selected depth of cut 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 (13) considering the constants α, β, γ and Ce calculated in Chapter 3.8.1 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.

Figure 34 represents the valid combination area for the operation.

![Figure 34: Example of implementation of the algorithm for longitudinal turning operation. Representation of the valid combination area.](image)
The initial cutting data considered is 130 [m/min] for the cutting speed and 0.2 [mm] 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]. The initial cutting data and the possible steps are presented in Figure 35. 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 33, until it reaches the optimal cutting data values, together with the values of ETL, UTL and RTL.
This chapter presents the analysis of the three main areas of this work. It also responds to the research questions presented in Chapter 1.

7.1 Analysis of the CAM programming work flow from the Lean perspective

In order to answer to the first research question in Chapter 1.3, and get an understanding of the CAM programming work flow and how the CAM Programmers conduct such process, CAM Programmers were interviewed. They were asked to explain their work flow step by step. With the data recollected from the interviews and the experience of the author, the CAM programming work flow was created as presented in Chapter 4.1. The interviewees had different visions about the projects and their different involvements were significant. Interviews were also used to confirm that the work flow used is similar to the one presented in Figure 2, but more details were needed for the Lean study.

Once a detailed CAM work flow was constructed, it was studied from the Lean perspective. Lean was used to identify possible inefficiencies in the CAM programming flow, as an answer to the second research question proposed in Chapter 1.3. This study showed that there were several key steps agglomerated into two areas, see Table 4. One area was concerning 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.

During the process planning steps of the CAM programming workflow, a rough estimation of the process was done based on the experience of the CAM Programmer and the involvement of other stakeholders, as shown in Tables 4 and 5. The selection of the different processes set the basis for productivity,
III. CONCLUSIVE CHAPTERS

7 Analysis

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During the process planning steps of the CAM programming workflow, a rough estimation of the process was done based on the experience of the CAM Programmer and the involvement of other stakeholders, as shown in Tables 4 and 5. The selection of the different processes set up the basis for productivity,
thereby its high relevance. In order to select the appropriate processes high experience is required, which motivates the involvement of the Process Expert during this step. The selection of the machines will set up the way the company uses its machine park, thereby its high relevance. To assure a uniform working load among all the machines, high skills are required and thereby the involvement of both the Process Expert and the Production Planner during the step. Tool selection and clamping system selection are both time consuming. Both steps contribute on the machining operations and the dimensional accuracy in the component, thus high importance and high skills required.

The CAM Programmer shall have considerable knowledge about the processes, the machining of different materials, the cutting tools, the cutting data selection, the availability of the machine park, and the logistics. The CAM Programmer shall also be able to calculate roughly the machining times and costs, which can represent a challenge for each new project. The inclusion of “concurrent engineering” into projects, has brought an increasing influence of the CAM Programmer at earlier stages of the projects. The presence of a CAM Programmer in earlier states of the project will influence in the decisions about production, dimensions and tolerances, assuring at the same time as low machining cost as possible. For instance, the presence of the CAM Programmer during the design phase of the project can influence the design in order to ease the machining preparation and machining process.

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 and time estimations for the whole process will therefore be rough estimations. The need of excessive iterations or steps back along the flow, as presented in Figures 14-19, is normally not included in the time plan and therefore might result in unwanted project delays. Every new project will raise new issues with their 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 a late step, the delay generated will be greater than a correction needed in an early step.

Further development of software features to simplify the CAM Programmer’s work shall be focused on simplifying the key steps that require high amount of time and experience as identified in Table 4. Several improvements can be proposed about the software used in order to simplify and reduce the programming time, and to keep the gained knowledge within the company.
Future software also needs to provide the possibility to simulate and verify as close as possible to reality, thereby decreasing the need for excessive real tests in the machine.

Other researches expressed that both technological and organizational improvements in any company leads to a better overall performance [59]. Therefore two approaches are suggested to continue improving the CAM programming flow, as represented in Figure 36.

The first approach is technological with the development and improvement of the different software. One possibility has been described in this thesis as the developed integrated optimization model or algorithm for cutting data selection. The second approach is organizational with two different proposals to reorganize the CAM Programmers. Both proposals allocate the more experienced people in some of the key areas and dedicating some of them to work with definition software. The CAM Programmers group is also suggested to be arranged either by processes or product features.

![Figure 36: Suggested approaches for continuous improvement of CAM programming work flow and company overall performance.](image)

### 7.2 Cutting tool utilization in production

A study of a CNC program from the MRR perspective and the tool life perspective was conducted in order to evaluate how well the cutting inserts are used in a production environment.
As an answer to the third research question proposed in Chapter 1.3, it was frequently found that the majority of the inserts were utilized far below their tool life limit, Figures 27-30. Therefore, those inserts are not used to their limits of Material Removal Rate and expected tool life. Those cutting tools are not used efficiently and thereby can be seen as an unnecessary addition to the total waste.

The inserts with low or even negative RTL values could be used on lower MRR values by decreasing either the cutting speed and/or the feed, illustrated in Figure 37. By doing this, the effective cutting time will increase, UTL decreases even though the UTL is kept as close to ETL as possible to ensure that the process stability and the surface integrity of the component produced is not affected.

![Figure 37: Illustration of a cutting tool with a low or negative RTL which utilization can be reduced by decreasing MRR, thereby ensuring process stability and surface roughness of the component produced.](image)

The inserts with high RTL values could either be used in a higher MRR value by increasing the cutting speed and/or the feed rate; or combine and re-order the operations as consecutive during the CAM programming process in order to use the insert in more operations, as presented in Figure 38. By doing this, it is possible to reduce the machining time; increase the UTL and keep RTL closer to zero; and increase the volume of material removed per insert. Other possible achievements are for instance the removal of a tool change and thereby the removal of non-cutting time; or the reduction of the number of cutting tools used for the machining of the component and therefore reducing tool waste and tool cost.

As consequence of the last achievements mentioned, the energy needed for the production of the cutting tool as well as the non-cutting time with that cutting tool are also spared.
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Figure 37: Illustration of a cutting tool with a low or negative RTL which utilization can be reduced by decreasing MRR, thereby ensuring process stability and surface roughness of the component produced.

The inserts with high values could either be used in a higher MRR value by increasing the cutting speed and/or the feed rate; or combine and re-order the operations as consecutive during the CAM programming process in order to use the insert in more operations, as presented in Figure 38. By doing this, it is possible to reduce the machining time; increase the and keep closer to zero; and increase the volume of material removed per insert. Other possible achievements are for instance the removal of a tool change and thereby the removal of non-cutting time; or the reduction of the number of cutting tools used for the machining of the component and therefore reducing tool waste and tool cost.

As consequence of the last achievements mentioned, the energy needed for the production of the cutting tool as well as the non-cutting time with that cutting tool are also spared.

Even in non-consecutive operations, the operations could be re-ordered during the CAM programming process to be able to use the tool to its maximal extent.

This implies that there is a 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.

### 7.3 Algorithm for cutting data selection

The investigations presented in this thesis show that there are both technological and organizational inefficiencies in today's manufacturing, and these present new opportunities for improvements. The investigations also show that the cutting tools are not used to their full extent with respect to MRR and tool life. As an approach to both assist the CAM Programmers during the cutting data selection and assure to optimal utilization of the cutting tools, an algorithm for cutting data selection was developed and has been presented in Chapter 6.2 as the answer to the fourth research question.

Maximal MRR is one of the objectives for a company that seeks to increase productivity and/or reduce costs. A common practice, once the cutting tool has been selected, is to select the maximum depth of cut, \( a_p \), possible, which is kept
constant throughout the operations. The two other variables to be selected for each tool and material combination are therefore feed, \( f \), and cutting speed, \( v_c \). Their combination will set up the working MRR level, as represented in Figure 5.

The cutting tool shall not be used above the mechanical and/or thermal load barrier, which could make them degenerate into early brittle and/or thermal failure. These barriers represent the initial constraints of the algorithm for both feed, \( f \), and cutting speed, \( v_c \), as presented in Figure 5. The aim is to use the cutting tool below those values so its wear will appear gradually and can be measured by its flank wear, as presented in Figures 8 and 11. \( VB_n \) is the tool wear criteria limit that will establish the constraint on tool life, \( T \) or \( ETL \), calculated as in Equation (14).

The integrated optimization algorithm for cutting data selection has two objectives. The first one is to maximize the Material Removal Rate. The second objective is to maximize tool utilization, in other words, minimize \( RTL \) as in Equations (17-18) or maximize \( UTL \) as in Equation (15).

There are constraints related to the machine or the cutting tool used during the cutting operation, such as maximal spindle speed, \( n_{max} \), maximal power provided by the machine, \( P_{max} \), machine efficiency in terms of power, \( \eta \), and nose radius of the cutting tool, \( r \), that will set up constraints for both cutting speed, \( v_c \), and feed, \( f \). As expressed in Equation (19), the power provided by the machine must be greater than the power required for the cutting operation, see Equation (6). In ideal conditions, the specific cutting force, \( k_c \), can be considered constant or not depend on \( f \), therefore the cutting power will be proportional to MRR, thus setting up a constraint for the maximal value of MRR as:

\[
P_{max} \eta = \frac{f a_p k_c v_c}{60} = \frac{MRR_{max} k_c}{60} \]  

Here the units are used as in the Nomenclature table in the beginning of the thesis. The minimum value of MRR is normally set up by the productivity that the company seeks; therefore the aimed MRR will be another constraint, as a lower limit for the valid cutting data combination. As presented in Figure 33, these constraints shall be more restrictive than the initial constraints presented in Figure 5, assuring that the cutting tool will wear continuously and not present an early failure.
7.3.1 Path towards the optimal cutting data combination

The initial cutting data combination used in the iterations is normally provided by the tool supplier, but can also 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 39, the variation in the cutting data can lead to a new combination that could be positioned in the same iso-MRR value, therefore even though the same productivity will be obtained, the tool life will vary along the iso-MRR. The new combination could be positioned in a different iso-MRR value as well. In the case that the new position is in a lower iso-MRR value, even though the machining time might also increase, the tool life will increase giving the opportunity to reduce the total machining time by decreasing the amount of tool changes. In the case that the new position is in a higher iso-MRR, even though the tool life will decrease, the machining time will also decrease providing the opportunity to reduce the total machining time by decreasing the machining time and therefore increasing the productivity.

Based on the above discussion, it is possible to appreciate the importance and difficulty of finding the balance between the two criteria, MRR and UTL, of the algorithm. In case of reducing MRR it is possible to extend the tool life until the operation is finished and thereby avoiding for example a tool change. In case of increasing MRR, and thereby reducing the cutting time, the tool life decreases as well.

The tool must be changed at specific points due to surface finishing requirements. Therefore the cutting data shall also be selected in order to be able to reach the tool change point without exceeding the tool life and at the same time utilizing the tool to its maximum extent.
7.3.2 Summary on the optimization algorithm

Summarizing and in analogy with how other researches [60] formulate the optimization models or algorithms, it is possible to formulate the integrated optimization algorithm for cutting data selection. The decision variables are feed, $f$, and cutting speed, $v_c$. Depth of cut, $a_p$, is not considered a decision variable in this algorithm because it is kept constant. There are two objective functions to maximize, MRR as presented in Equation (1) and tool utilization as presented in Equation (15). The mechanical and thermal barriers could be considered as boundary conditions. Surface roughness, $R_a$, maximal spindle speed, $n_{max}$, maximal power provided by the machine, $P_{max}$, $RTL$ and minimum aimed MRR could be considered as constraints of the algorithm.

Finally, other researchers [61] have presented interesting ways to improve the cutting tool utilization, which can further be implemented in the search of increased production rate and decreased energy consumption.

7.4 Industrial implementation of the algorithm

The integrated optimization algorithm for cutting data selection is actually under development for industrial implementation in the CAMALEONT project. The objective is to integrate the algorithm into existing CAM systems to support the CAM Programmer during the cutting data selection. Figure 40 shows an
example of how the algorithm can be seen by the CAM Programmer in its industrial implementation in an existing CAM system. The example shows the tool life analysis of six tools, where two are used over their expected tool life. As discussed during this work, for the cutting tools that has low or negative RTL, the cutting data shall be adjusted to a lower MRR value. The cutting tools that have high RTL, the cutting data shall be either adjusted to a higher MRR value, or spared and used for another operation.

Figure 40: 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 here. 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 workflow has been described with enough detail as to be able to perform an analysis from the Lean perspective. Thereby this investigation allowed the identification of the key steps, the inefficiencies and the involvement of the different stakeholders along the workflow.

The key steps identified in the CAM programming process from the Lean perspective can be grouped in 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, Figures 27-30, on average approximately 50%. Therefore, those inserts can be seen as an unnecessary addition to the total waste.

In order to ease the CAM Programmer work, 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, 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 . Therefore the selection of cutting data parameters can be oriented towards productivity and better plan the several tool changes required.
8 Conclusions

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Discussion and Further work

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

9.1 Discussion

According to the 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. 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 inserts were utilized below their tool life limit. Therefore, those inserts can be seen as an unnecessary addition to the total waste. When programming, the utilized tool life, shall be kept as close as possible to the expected tool life, . When reaching low or even negatives values of the remaining tool life, , the cutting data shall be changed to a lower MRR level. On the other hand, when reaching high values of remaining tool life, , the cutting data shall be changed to a higher MRR level, or reorder the operation to fully utilized the inserts.

Software improvements shall be made towards a user friendly environment, e.g. adding features that will simplify the work of the CAM Programmer and with the possibility that the programmer can see and modify the different variables. In order to ease the CAM Programmer work, an integrated optimization algorithm for cutting data selection based on maximal MRR and tool utilization has been presented. Thus the selection of cutting data parameters can be oriented towards productivity and better plan the several tool changes required. Therewith, it is possible to provide the CAM Programmer with an optimal cutting data, reducing the number of needed iterations to reach the desired level of productivity and thus, also the time required for the development of the NC program.
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To summarize, and as a result of this work, it is possible to improve the cutting tool utilization. As a consequence of this, it is possible to increase the amount of volume of material removed per insert, decrease the remaining tool life left on the cutting tools, decrease the amount of tool changes, decrease the machining time and decrease the number of tools used. From this work, it is also possible to ease the CAM programming work by reducing the amount of needed iterations. As a consequence, by a better re-utilization of the gained knowledge, the development time of the CAM programs of new projects can be reduced. As further consequences, a more efficient utilization of the resources will bring cost reductions.

9.2 Further work

In order to continue the work here described, and in the search of continuing the development of an integrated model, see Figure 41, further work is proposed here.

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

The simplifications taken, how the problem is studied, its optimization, the input data and even the initial cutting data combination might affect the validity of the proposed algorithm; therefore verification and validation of the algorithm is needed and is proposed as future work.

Future development of CAM systems is oriented to new, user friendly features which shall continue the trend of software integration and the addition of more features. Thereby the considerable relevance of new features that will support the CAM Programmer during the generation of tool paths in combination with cutting mechanics, tool wear and cost. Therefore the optimization model can be further developed by including cost which is proposed as future work.
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Figure 41: Present and future work representation
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Analysis and direct optimization of cutting tool utilization in CAM

The search for increased productivity and cost reduction in machining can be interpreted as the desire to increase the material removal rate, MRR, and maximize the cutting tool utilization. The CNC process is complex and involves numerous limitations and parameters, ranging from tolerances to machinability. A well-managed preparation process creates the foundations for achieving a reduction in manufacturing errors and machining time. Along the preparation process of the NC-program, two different studies have been conducted and are presented in this thesis. One study examined the CAM programming preparation 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.

The material removal rate is defined as the product of three variables, namely the cutting speed, the feed and the depth of cut, which all constitute the cutting data. Tool life is the amount of time that a cutting tool can be used and is mainly dependent on the same variables. Two different combinations of cutting data might provide the same MRR, however the tool life will be different. Thereby the difficulty is to select the cutting data to maximize both MRR and cutting tool utilization. A model for the analysis and efficient selection of cutting data for maximal MRR and maximal tool utilization has been developed and is presented. The presented model shortens the time dedicated to the optimized cutting data selection and the needed iterations along the program development.