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Digitalization in the Field of Machine Tools and Tool Management

DOCTORAL THESIS
to achieve the university degree of
Doktor der Technischen Wissenschaften

submitted to

Graz University of Technology

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Graz, May 2021

AFFIDAVIT

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Thanks

I would like to thank everyone who made this thesis possible.

First of all, I would particularly like to highlight Dipl.-Ing. Dr.techn. Rudolf Pichler, who gave me the opportunity to write this thesis as part of my employment as a research associate at the Institute of Production Engineering at Graz University of Technology. I really appreciate the supervision of my thesis, his trust in me and the freedom he gave me for conducting my research.

I would also like to thank Univ.-Prof. Dipl.-Ing. Dr.techn. Franz Haas for the opportunity to work at his institute and for taking over the supervision of my thesis. I particularly appreciate his calm nature and his technical support during my research activities. Also, I would like to thank Univ.-Prof. Dipl.-Ing. Dr.techn. Friedrich Bleicher for being part of the thesis committee and for the review of my thesis. Furthermore, I would like to thank Univ.-Prof. Dipl.-Ing. Dr.techn. Michael Heiss, who is mainly responsible for the excellent cooperation with Siemens. Without his support this thesis would not have been possible in this form.

In addition to Siemens, I am very grateful for the good cooperation with TCM International, Zoller Austria, JANUS Engineering and SPINNER Werkzeugmaschinenfabrik.

Above all, I would like to highlight the technical support provided by Johannes Wurzinger, Peter Gantner, Dipl.-Ing.(FH) Hannes Trink, Dipl.-Ing. Gerhard Krubner, Martin Treichler, Stefan Benedukt, Ing. Johannes Resch and Christoph Werner.

I am also grateful for the good cooperation with my colleagues Dipl.-Ing. Stefan Trabesinger, Dipl.-Ing. Daniel Stampfl, Dipl.-Ing. Dr.techn. Markus Brillinger, Dipl.-Ing. Dr.techn Christian Höller and Philipp Schwemberger.

In the context of my work and research, I was able to supervise several students. I would like to highlight Dipl.-Ing. Maximilian Müller, Dipl.-Ing. Andre Butzerin, Dipl.-Ing. Daniel Vallant and Christoph Rockenschaub who have made valuable contributions to my thesis.

I also want to thank my brother Alexander who also contributed to the success of this thesis and my parents who supported me financially.

Finally, I would like to extend my gratitude to my girlfriend Sara.
I could not have done this thesis without you and I am honored to share my life with you.

Thank you all.

Kurzfassung

Die vorliegende Arbeit beschäftigt sich mit dem Thema Digitalisierung im Bereich der Werkzeugmaschinen und des Werkzeugmanagements. Das Forschungsziel dieser Arbeit ist die Erarbeitung und anschließende Optimierung einer CAD-CAM-CNC Prozesskette, welche dem Stand der Technik entspricht und eine besondere Eignung für kleine und mittlere Unternehmen sowie kleine Losgrößen bis hin zur Losgröße 1 Fertigung, aufweist.

Neben der theoretischen Betrachtung wurde die gewählte Prozesskette in der smartfactory@tugraz, der Lernfabrik des Institutes für Fertigungstechnik an der Technischen Universität Graz, unter realen Bedingungen implementiert. Diese tatsächliche Umsetzung lieferte sehr viele Erkenntnisse, welche zur Erstellung eines Reifegradmodells verwendet wurden, welches eine vorteilhafte Implementierungsreihenfolge der gesamten Prozesskette beschreibt.

Um etwaige Schwachstellen der gewählten Prozesskette aufzuzeigen, wurde mittels der Fehlermöglichkeits- und Einflussanalyse die gesamte Prozesskette untersucht. Hierbei stellte sich heraus, dass vor allem die Wahl von Schnittdaten, sowie die Erstellung von digitalen Werkzeugkomponenten in Bezug auf mögliche Schäden an Werkzeugmaschinen, als sehr kritisch eingestuft werden kann. Des Weiteren wurde eine Umfrage durchgeführt, welche allgemeine Herausforderungen des behandelten Themengebietes hervorheben soll. Ausgehend aus den Ergebnissen der Fehlermöglichkeits- und Einflussanalyse und der Umfrage, wurde der Bedarf nach einer neuen Methode festgestellt, welche die Datenbank einer Toolmanagement Software automatisch mit korrekten Daten befüllen kann.

Ein Closed-loop Manufacturing Ansatz wurde hierbei entwickelt, welcher zur Erfassung sowie Speicherung von validierten Schnittwerten dient. Hierbei wurde mittels eines entwickelten Digitalen Modells eine Methode geschaffen, um SOLL-Werte an eine Werkzeugmaschine zu übertragen, welche anschließend durch eine ebenso entwickelte Methode mit den IST-Werten ausgelesen werden können. Nach einer Evaluierung können die Werte in eine dafür vorgesehene Datenbank gespeichert und für nachfolgende Fertigungsplanungen zur Verfügung gestellt werden. Um die zuvor beschriebenen Fehlerquellen zu reduzieren, wurde des Weiteren eine Applikation entwickelt, welche eine Verifizierung der verwendeten Werte ermöglicht.

Außerdem wurde eine Methode entwickelt, um digitale Werkzeugkomponenten, ausgehend von einem 3D-Scan, automatisch in eine Toolmanagement Datenbank zu speichern. Dies wurde durch eine entwickelte Applikation erreicht, welche die gescannte Kontur anhand von bestimmten Parametrierungen ausliest und die zugehörigen Zahlenwerte in ein tabellarisches Format überträgt. Diese Werte können anschließend von einer Toolmanagement Software eingelesen werden.

Durch die entwickelten Methoden kann der hohe Aufwand in Bezug auf Digitalisierung im Bereich des Toolmanagements reduziert und zusätzlich die Fehlerrate reduziert werden.

Abstract

The present thesis deals with the topic of digitalization in the field of machine tools and tool management. The research objective of this work is the development and subsequent optimization of a CAD-CAM-CNC process chain, which meets the state of the art and is particularly suitable for small and medium-sized enterprises as well as small lot sizes up to lot size 1 production.

In addition to the theoretical consideration, the selected process chain has been implemented under real conditions in the smartfactory@tugraz, the learning factory of the Institute of Production Engineering at Graz University of Technology. This actual implementation provided a lot of knowledge, which has been used to create a maturity model that describes an advantageous implementation sequence for the entire process chain.

In order to identify the problem areas in the selected process chain, the entire process chain has been examined using the Process - Failure Mode and Effects Analysis. The results suggest that the choice of machining data and the creation of digital tool components with regard to possible damage to machine tools can be classified as highly critical. Moreover, a survey has been carried out to identify the general challenges of the subject area. Based on the results of the Process - Failure Mode and Effects Analysis and the survey, the need for a new method which can fill the database of a tool management software with correct data automatically has been detected.

A Closed-Loop Manufacturing approach has been developed, which is used to record and store validated machining data. By using a developed Digital Model, a method was created to transfer TARGET values to a machine tool, which can then be read out with the ACTUAL values using an equally developed method. After an evaluation, the values can be saved in a database provided for this purpose and made available for subsequent production planning. In order to reduce the sources of error, an application, which enables the verification of the used values, has also been developed.

Furthermore, a method to save digital tool components in a tool management database based on a 3D scan has been developed. This has been achieved through a developed application which reads out the scanned contour based on certain parameterizations and transfers the associated numerical values in a tabular format. These values can then be read in by a tool management software.

Finally, it can be said that these developed methods reduce the high level of effort involved in digitalization in the area of tool management. What is more, the error rate can also be reduced significantly.

Contents

Figures

Tables

Abbreviations

API	Application Programming Interfaces
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CC	Custom command
CCF	Controller configuration file
CF	Confer
CSW	Coordinate System Workpiece
CLDATA	Cutter-Location Data
CLM	Closed-Loop Manufacturing
CNC	Computerized Numerical Control
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
CSE	Common Simulation Engine
CSV	Comma-separated values
D	Detection
DIN	Deutsches Institut für Normung
DM	Digital Model
DNC	Direct Numerical Control
DS	Digital Shadow
DT	Digital Twin

ERP	Enterprise-Resource-Planning
FMM	Feature-Macro Mapping
FRF	Frequency Response Function
GUD	Global User Data
LE	Large Enterprise
MDL	Machining Data Library
MTB	Machine Tool Builder
MCF	Machine configuration file
MCS	Mounting Coordinate System
MES	Manufacturing Execution System
NASA	National Aeronautics and Space Administration
NC	Numerical Control
O	Occurrence
OPC UA	Open Platform Communications Unified Architecture
PDM	Product Data Management
PFMEA	Process - Failure Mode and Effects Analysis
PLM	Product Life-cycle Management
PMI	Product Manufacturing Information
PP	Post-processor
QR	Quick Response
RFID	Radio-Frequency Identification
RPN	Risk Priority Number
UDE	User Defined Event
S	Severity
SFC	Shop Floor Connect for Teamcenter

SME	Small and Medium Enterprise
SRAM	Static Random Access Memory
STEP-NC	Standard for the Exchange of Product Model Data - Numerical Control
TDS	Tool Dispensing System
TMS	Tool Management Software
USB	Universal Serial Bus
VBA	Visual Basic for Applications
VDI	Verein Deutscher Ingenieure
VNCK	Virtual Numerical Control Kernel
XML	Extensible Markup Language

Variables

C_T	Theoretical Tool Life at a Cutting Speed of One Meter Per Minute
k	Slope of the Tool Life Line
K_{ML}	Machine Tool and Labor Costs
K_{Tool}	Tool Costs per Tool Life
T	Tool Life
$t_{exchange}$	Tool Change Time
v_c	Cutting Speed
$v_{c_{oc}}$	Cost-Optimized Cutting Speed
$v_{c_{ot}}$	Time-Optimized Cutting Speed

1. Introduction

On the one hand, digitalization of a company is mainly characterized by the optimization of internal processes and the creation of new products, services or business models on the other. In the field of modern production, digitalization enables all production-relevant elements to be connected and thus the underlying processes to be optimized.[1] Furthermore, the simulation of technical systems and processes is considered one of the key technologies for product development and production planning. The aims of computer aided production planning are the achievement of error-free production processes, the optimization of machining times and overall the improvement of the efficiency of the entire production process.[2,3] The implementation of elements with regard to Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computerized Numerical Control (CNC) and tool management in a company, require a lot of effort. In addition, these products, which are currently available in a wide variety of forms, appear extremely complicated and complex. This combination of circumstances makes the introduction of these products difficult, especially for small and medium-sized enterprises (SMEs), which are generally equipped with more limited financial and human resources than large enterprises (LEs). [4,5]

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[1] cf. Ematinger, (2017).

[2] cf. Storm, (1993), pp.47-49.

[3] cf. Vajna et al., (1994), pp.227-296.

[4] cf. Kief et al., (2017), p.648.

[5] cf. Hehenberger, (2011), pp.118-122.

1.1. Research Objective

The research objective of this thesis is to elaborate on a state of the art CAD-CAM-CNC process chain, which should be specifically suitable for SMEs and small lot sizes up to lot size 1 production. Based on the chosen process chain, a technically optimal implementation sequence will be worked out.

In addition to the theoretical elaboration of this process chain, it will be validated based on an actual implementation at smartfactory@tugraz, which is the Learningfactory at the Institute of Production Engineering at Graz University of Technology. Afterwards the selected process chain will be examined for specific and general challenges and problem areas. These challenges and problem areas are then to be solved through further developments.

1.2. Research Methodology

After an extensive study of literature, the selected process chain was fully implemented with the help of experts from the industry. A maturity model was then developed to determine an order of implementation for the selected process chain. Then, the Process - Failure Mode and Effects Analysis (PFMEA) method was primarily used to evaluate the selected process chain. In addition, discussions were held with experts and users from the industry. Based on these discussions, a questionnaire was generated, which was then issued in relevant forums on the Internet. Relevant problem areas were identified based on both results. After this problem-finding process, possible solution approaches were developed and implemented.

1.3. Definition of Terms

As there is a very high number of different definitions of digitalization terms used in this work, the following subsections clarify how certain terms are to be understood in the context of this thesis. It should be emphasized that the simulation of a machine tool is neither viewed as a Digital Twin (DT) nor as a Digital Shadow (DS), as explained below.

1.3.1. Digital Twin

Due to the popularity and relevance of the term DT, a lot of consideration was given to this topic within this work. For this reason, in addition to the different definitions and subdivisions, the origin of this specific term is also discussed.

History

The term "twin" originates from the Apollo program of the National Aeronautics and Space Administration (NASA). Two spaceships were built and while one of them was in space, the one on the ground was used to recreate the conditions. Over time, more and more attempts were made to digitally represent the "twin". The first definition of a DT coined in 2003 by Michael Grieves (Florida Institute of Technology), but he attributed this term to the joint work with John Vickers (NASA).[6,7]

In this first definition, the term DT was described according to the following three dimensions:

- Existing physical entity
- Digital counterpart
- Bidirectional connection of data and information

Due to its high relevance, the term DT has found its way not only into the area of the simulation of an aircraft, but also into the automotive, oil, gas and health-care industries. Today, there are countless different definitions of the term DT, which have become established in all kinds of areas. Tables 24 and 25, which are attached in the appendix, show the most relevant examples of DT's various definitions, listed according to the views of universities and enterprises. As in the two tables listed, there is no uniform definition of a DT. Another complicating factor in regard to a uniform definition is, that in addition to different definitions of the term DT, there are also different subdivisions of it. For instance, Grieves and Vickers propose a subdivision of "Digital Twin Prototype", "Digital Twin Instance" and "Digital Twin Environment", while Siemens uses a subdivision of "Product Digital Twins", "Production Digital Twins" and "Performance Digital Twins". These subdivisions are described more in detail in the appendix of this thesis. [8,9]

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[6] cf. Tao et al., (2019), p.5.

[7] cf. Grieves, (2015).

[8] cf. Grieves / Vickers, (2017), pp.94-95.

[9] cf. Siemens, (2019c), Online-source [23.02.2020].

The original definition of a DT by Grieves and Vickers is rather unsatisfactory when it comes to the various definitions and subdivisions. It seems very useful to make a distinction according to different areas of application. However, a discussion about various forms of subdivisions appears to be unsuitable, since there is still no standardized definition of the generic term DT. For this reason, the term DT is not subdivided within this work.

Based on the original definition of a DT, a digital counterpart, which behaves exactly the same as the physical object, is not considered a DT, if the physical object does not exist. Such an example can be seen with a "Digital Twin Prototype", but not with a pure DT. For these reasons, the following definition was established within this work on the basis of selected sources. [10,11,12,13]

Definition of a Digital Twin in this Thesis

The digital counterpart describes the macrostructure as well as the relevant microstructure of the physically existing object. In addition, all control-relevant processes must be precisely digitally mapped. Should the physical object achieve a status that the digital counterpart considers as critical, the digital counterpart must be able to act as a control instance for the physical object. The bidirectional transfer of data and information must be automated and in real-time. Whether the real-time is hard, soft or firm depends on the area of application. All recorded data must be saved and, above all, included in the calculation of the microstructure and, in another form, also in the calculation of the macrostructure.

Figure 1 illustrates this definition graphically:

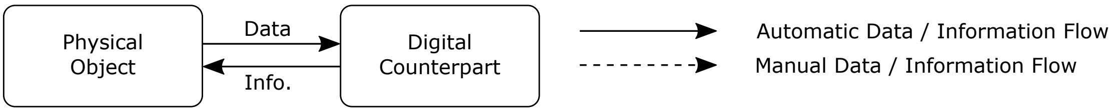

Figure 1.: Definition of a Digital Twin in this thesis
Source: Kritzinger et al. (2018).

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[10] cf. Kritzinger et al., (2018).
[11] cf. Riedlsperger et al., (2020).
[12] cf. Schmid, (2018), pp.26-34.
[13] cf. Grieves / Vickers, (2017).

Example of a Digital Twin According to the Definition Used in this Thesis

The definition of a DT, as used in this thesis can be illustrated by the example of a wind turbine. There is a digital counterpart to the physically existing turbine, which reproduces the physical object at macroscopic and microscopic level. Based on the sensor data of the physical turbine, the digital counterpart is supplied with the values of the sensors. Due to this constant data update, the digital turbine exactly reflects the operating status of the real turbine. If, for example, the real turbine reaches a critical status, the digital counterpart of the turbine can calculate a precise forecast and initiate any countermeasures. [14,15,16,17]

1.3.2. Digital Shadow

Next to the DT and its various possible subdivisions, the term DS is being used increasingly. DS is often equated with DT, but there is an essential difference.

Definition of a Digital Shadow in this Thesis

"The digital shadow is the sufficiently accurate digital representation of a product or a process with the purpose of creating a real-time analysis base for all relevant data." [18,19]

Based on this definition, a DS is mainly the storage of metadata. These data need to be stored with sufficient accuracy. The accuracy of these data depends on the area of application. The data are then stored automatically in a database and made available for subsequent evaluation procedures. Another striking difference to the DT is that the digital counterpart does not automatically transfer information to the physical object. This information is only transferred manually.
Figure 2 illustrates this definition graphically:

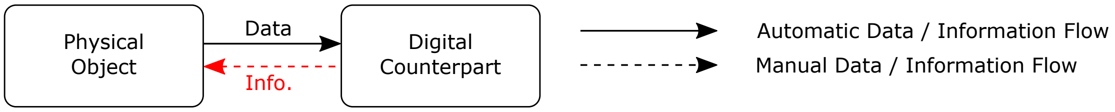

Figure 2.: Definition of a Digital Shadow in this thesis
Source: Kritzinger et al. (2018).

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[14] cf. Rolls-Royce, (2019), Online-source [28.02.2020].
[15] cf. Rolls-Royce, (2018), Online-source [28.02.2020].
[16] cf. Energy 4.0, (2017), Online-source [15.07.2020].
[17] cf. Juschkat, (2018), Online-source [15.07.2020].
[18] Tönnes et al., (2018).
[19] Bauernhansl, (2016).

Example of a Digital Shadow According to the Definition Used in this Thesis

A production line of a company can be used as an example for a DS. On this production line, for example, tool wear can be higher at certain times. If these wear data are stored in a database, these data can be used for possible future predictions. [20]

1.3.3. Digital Model

Neither the aforementioned definition of a DT, nor that of a DS are applicable to the field of CAM. As defined in the subsequent definition, a digital counterpart of a machine tool in a CAM environment in this thesis is defined as a Digital Model (DM). [21,22,23,24]

Definition of a Digital Model in this Thesis

"A Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital counterpart. The digital representation might include a more or less comprehensive description of the physical object. These models might include, but are not limited to, simulation models of planned factories, mathematical models of new products, or any other models of a physical object, which do not use any form of automatic data integration." [25]

Figure 3 illustrates this definition graphically:

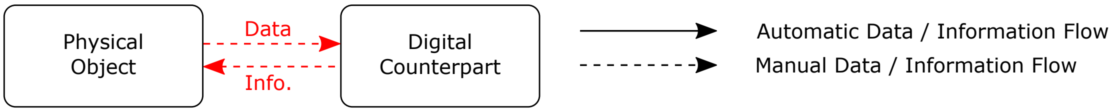

Figure 3.: Definition of a Digital Model in this thesis
Source: Kritzinger et al. (2018).

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[20] cf. Wohlfeld et al., (2017).
[21] cf. Siemens AG, (2019b).
[22] cf. Tao et al., (2017).
[23] cf. Tao et al., (2018).
[24] cf. Vachálek et al., (2017).
[25] cf. Kritzinger et al., (2018).

Example of a Digital Model According to the Definition Used in this Thesis

As an example of a DM, a simple CAD model of a component can be provided. Every mathematical calculation model also serves as an example. **The digital representation of a machine tool in a CAM environment can also be considered as a DM. An improved simulation method, such as an emulated or even simulated control, which is discussed in more detail in Subsection 2.2.2, does not result in a DT.**

1.3.4. Closed-Loop Manufacturing

Originally, the term Closed-Loop Manufacturing (CLM) was introduced as "Closed Loop Machining" and was used to describe a machine tool that was equipped with a built-in measuring device. With this measuring device, the machine tool could measure the previously manufactured components and, if necessary, rework them independently.[26] The concept of a feedback loop as described in "Closed Loop Machining" is also used in CLM. **The difference, however, is that CLM is not one feedback loop in a machine tool, but several in the entire product life cycle. The data obtained can then be used to optimize future products.** [27,28]

1.3.5. Lot Size 1 Production

"The catchphrase "lot size 1" describes a production scenario in which a completely order-oriented production with individualized products is realized." [29]
Regarding the definition used, it should be noted that the number 1 does not necessarily have to be adhered to. Rather, the ratio of set-up and programming effort to the actual production time for a desired batch is more important.

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[26] cf. Kennedy / Ford, (2003).
[27] cf. Zainzinger / Heiss, (2020).
[28] cf. Siemens PLM Software, (2018).
[29] cf. Reinhart, (2017), p.295.

1.3.6. Cyber-Physical Systems

The extension of physical systems with sensors and actuators as well as embedded software that is capable of data processing and independent communication create a so-called Cyber-Physical System (CPS). The characteristics of a CPS can be summarized as follows: [30,31,32]

- Collect data using sensors
- Act on processes with actuators
- Evaluate and save data
- Interact with the digital and real world
- Connected to each other / globally via digital communication devices
- Use data and services available worldwide
- Have human-machine interfaces

Especially in manufacturing companies, the application of a CPS in the production area is called Cyber-Physical Production System (CPPS). Generally, the same characteristics and principles of a CPS are used, but mostly in relation to production processes. This includes, for example, apart from the actual production, the processes of the supply chain, quality management, etc. The structure of a CPPS is different in every company, but the individual parts are always the same: The physical part, the cyber-physical part and the linkage part. The physical part of a CPPS is mainly represented by the hardware in the shop floor, such as machine tools or presetting and measuring machines etc. The cyber-physical part of a CPPS mainly consists of software for planning, modelling, analyzing or simulation etc., followed by the business administration tools Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES). The linkage part includes the setting and matching of connection standards and protocols. Various middleware systems such as Shop Floor Connect for Teamcenter (SFC) can be named as an example. [33,34,35]

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[30] cf. Reinhart, (2017), p.XXXIV.

[31] cf. Westkämper / Löffler, (2016), pp.157-161.

[32] cf. Neugebauer, (2018), pp.197-207.

[33] cf. Pichler / Gerhold, (2020).

[34] cf. Vogel-Heuser et al., (2017a), p.45.

[35] cf. Vogel-Heuser et al., (2017b), p.75.

2. State of the Art of Different CAD-CAM-CNC Process Chain Elements

This chapter describes the state of the art of all elements of the CAD-CAM-CNC process chain that are considered relevant. The process chain to answer the first part of the research objective was selected from these elements and is described in the following chapter.

2.1. Computer Aided Design

CAD describes the general support of all construction activities (2D and 3D) through computer aids. In addition to geometry generation, this includes all other activities relating to calculation, simulation and information acquisition for the purpose of creating a product model. An important point of the state of the art is the possibility of parameterization, which enables these models to be influenced by numerical values and thus change processes, the creation of variants and the repeated use of similar models. In addition, CAD models are generated associatively, which means that dependencies can be assigned under the different parameters of the model. If CAD data are saved in a standard file format, they lose the possibility of adapting the parameterization and associativity. For this reason, some CAD systems also offer the option of direct modeling. This allows CAD data to be changed and thus adapted by simply shifting surfaces of the bodies. Another important development of CAD systems is the possibility of adding Product Manufacturing Information (PMI) to CAD data. Using these PMIs, information relevant to production can be attached directly to the CAD model. This has the advantage that a 2D drawing is not necessary for production planning. [1,2,3]

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[1] cf. Hehenberger, (2011), p.120.

[2] cf. Kief et al., (2017), p.705.

[3] cf. Scheidegger, (2016), p.190.

2.2. Computer Aided Manufacturing

In addition to the possibilities of programming a machine tool by entering Numerical Control (NC) code, which is standardized in DIN 66025 or the graphically supported workshop-oriented programming, a machine tool can also be programmed by using a CAM software. The main advantage of a CAM software is that a machine tool can be used for machining during the programming process. Another advantage is that even complex geometries can be programmed. Additionally, a complete collision check of the generated NC code can be performed in advance under certain conditions (Subsection 2.2.2.2). A CAM software can also be used to check the NC code regarding correct syntax (Subsection 2.2.2.3). After programming on a CAM software, a source program is created which describes all planned processing steps of the machine tool in a standardized (DIN 66215) Cutter-Location Data (CLDATA) format. To make sure that the planned machining steps can be read by a machine tool, the CLDATA code has to be converted into a machine-specific NC code. With a few exceptions (Subsection 2.2.1.3), this translation process is carried out by a post-processor (PP). Since almost all control manufacturers use non-standardized, specific commands in their own syntax next to the standardized commands, every PP must be adapted to the respective machine tool, which is explained in more detail in Subsection 5.2.4. An example of an NC code that matches the CLDATA code of Figure 4a is shown in Figure 4b. [4,5,6,7]

```
SPINDL / RPM, 5000.000000, CLW                 | S5000 M3
RAPID                                          |
GOTO / 0.00000000, 0.32487729, 10.00000000     | G0 X0 Y0.32487729 Z10.
RAPID                                          |
GOTO / 0.00000000, 0.32487729, 2.00000000      | G0 Z2.0
FEDRAT / 300.000000, MMPM                      |
GOTO / 0.00000000, 0.32487729, -1.00000000     | G94 G1 Z-1.0 F300.
GOTO / 0.00000000, 0.32487729, -1.00000000     |
GOTO / 0.00000000, 1.32487729, -1.00000000     | G1 Y 1.32487729
```

(a) CLDATA code (b) NC code

Figure 4.: Example of a matching CLDATA and NC code
Source: Hehenberger (2011), p.148.

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[4] cf. Hehenberger, (2011), p.84.

[5] cf. VDI 4499, (2008).

[6] cf. Siemens AG, (2018b).

[7] cf. Kief et al., (2017), p.758.

2.2.1. Coupling Variants of CAD-CAM Systems

In order to plan the manufacturing processes in a CAM software, the desired component must first be created in a CAD software. As shown in Figure 5, a basic distinction is made between three different types of CAD-CAM coupling variants. The different advantages and disadvantages of these variants are described in the following subsections. [8,9,10]

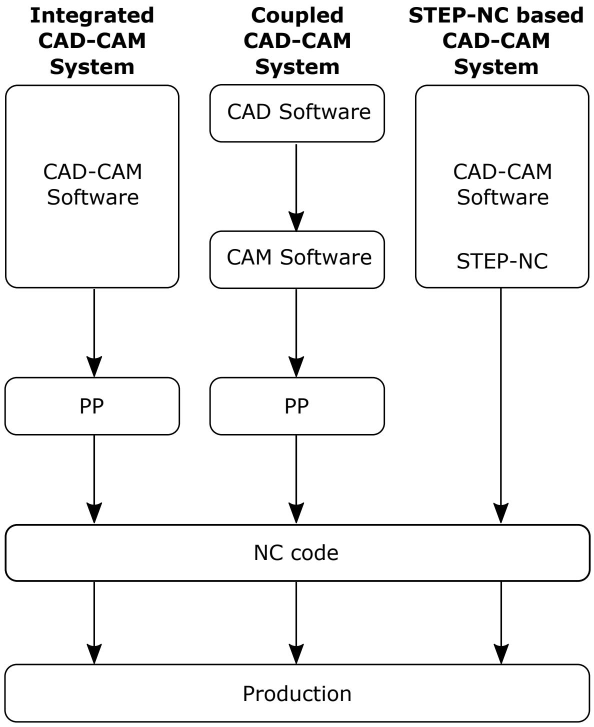

Figure 5.: Coupling variants of CAD-CAM systems
Source: Hehenberger (2011), p.147. and
Kretzschmann (2010), p.16

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[8] cf. Hehenberger, (2011), p.147.

[9] cf. Kretzschmann, (2010), p.16.

[10] cf. Brillinger et al., (2019).

2.2.1.1. Coupled CAD-CAM System

CAD and CAM software are two different software products that generally communicate via neutral data formats. An advantage of this coupling variant is the simple integration of this system into an existing system architecture of a company. The major disadvantage of this variant is the neutral data format and the resulting regulations. These manifest themselves, for example, in a loss of data. If, for example, a threaded hole is designed in a non-neutral data format, information of the core diameter and the pitch exist in addition to the nominal diameter and the depth of the thread. If it is saved in a neutral data format, all data about the thread are lost and there is only information about the nominal diameter and the general depth of the threaded hole. Any further disadvantages result from the fact that CAD and CAM software are two different systems. As an example, a modification of the component to be produced can be named. The effort that has to be made to modify a component is a lot higher than if CAD and CAM software were used within an integrated system. [11]

2.2.1.2. Integrated CAD-CAM System

Integrated CAD-CAM systems are a combination of both types in one single software product. The communication takes place via the internal data format and not via a neutral data format as in coupled systems. The advantage with this method is that no data loss occurs. A further advantage is that any modifications to components to be produced can be done very quickly. This is a result of their easy updateability due to the absence of data loss. A disadvantage of an integrated CAD-CAM system is its implementation effort. If a company decides to implement an integrated system when a CAD and / or CAM software is already implemented, both software products may have to be replaced. [12,13]

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[11] cf. Hehenberger, (2011), pp.142-147.

[12] cf. Hehenberger, (2011), pp.146-147.

[13] cf. Kemptner, (2016).

2.2.1.3. STEP-NC Based CAD-CAM System

As already mentioned, most CAM software products use the internal CLDATA format. As discussed above, machine tools require NC code. The basic problem concerning a program created by a CAM software and translated into an NC code by a PP is the lack of bidirectionality. If a change is made in a CAM program and then a new NC code is generated, the change is transferred. However, if the NC code is changed, there is not any form of data transfer to the CAM program and none to the CAD data either. Since a fine tuning of the NC code is often done, a critical data loss occurs. The "Standard for the Exchange of Product Model Data - Numerical Control" (STEP-NC) has been developed to counteract this problem. STEP-NC is a standard (ISO 14649) currently being developed, which describes a data model that can store not only the geometry of the workpiece, but also the tool paths and associated information relating to the manufacturing process. The same file, which contains the CAD and CAM data, can then be translated into NC code without a PP. A conversion between different formats with the associated problems is no longer necessary. Such object-oriented STEP-NC files contain the necessary information not only in individual blocks, but in larger logical units. Figure 6 shows an excerpt of such a STEP-NC program. In theory, this should enable a bidirectional data flow between the CAD-CAM software and the NC code. Whether the STEP-NC standard will assert itself cannot be estimated at present. For this reason, STEP-NC is not considered further in this thesis. [14,15,16]

---

[14] cf. Brecher et al., (2013).

[15] cf. Hehenberger, (2011), pp.152-153.

[16] cf. Xu / Nee, (2009), pp.222-223.

```
// File header
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(...');
FILE_NAME(...');
FILE_SCHEMA((...);
ENDSEC;
DATA;
// Workpiece and work plan
#1=PROJECT('Drilling',#2,(#3));
#2=WORKPLAN('Work plan',(#4),$,#5);
#3=WORKPIECE('Workpiece 1',#6,0.01,$,$,#8,());
// Processing steps
#4=MACHINING_WORKINGSTEP('Drilling',#13,#16,#17);
#5=SETUP('Clamping',#30,#34,(#37));
#6=MATERIAL('St50','Steel',(#7));
#7=PROPERTY_PARAMETER('E210000 N/MM^2');
#8=BLOCK('Block',#9,110.000,110.000,80.000);
#9=AXIS2_PLACEMENT_3D;
// Geometrical information
#10=CARTESIAN_POINT('',(-5.0,-5.0,-5.0));
#11=DIRECTION('',(0.0,0.0,1.0));
#12=DIRECTION('',(1.0,0.0,0.0));
#13=PLANE('',#14);
#14=AXIS2_PLACEMENT_3D('',#15,$,$);
#15=CARTESIAN_POINT('',(0.0,0.0,60.0));
// Manufacturing features
...
```

Figure 6.: Example of a STEP-NC Code
Source: Hehenberger (2011), p.153.

2.2.2. Different CAM Simulation Methods

The different methods of CAM simulation can be qualitatively classified as follows: [17,18]

- CAM simulation **without consideration of the control** of the machine tool
- CAM simulation with **emulated control** of the machine tool
- CAM simulation with **simulated control** of the machine tool

The differences between these methods are explained in the following subsections by means of deliberately erroneous examples. These examples are intended to show which errors can be found with which method.

---

[17] cf. Kief et al., (2017), pp.649-651.

[18] cf. Oehler, (2016), pp.7-12.

2.2.2.1. CAM Simulation without Consideration of the Control of the Machine Tool

The simplest form of a CAM simulation is the CAM simulation without consideration of the respective control of the machine tool later used. The previously generated machining paths in the CAM software are described during the simulation in the internal CLDATA format. This simulation method is often used at an early stage of planning of the production process, as it is not yet necessary to define the machine tool later used. It is not necessary to define a clamping device either. The tools, however, must be selected. Figure 7 shows an example of this simulation method. [19,20]

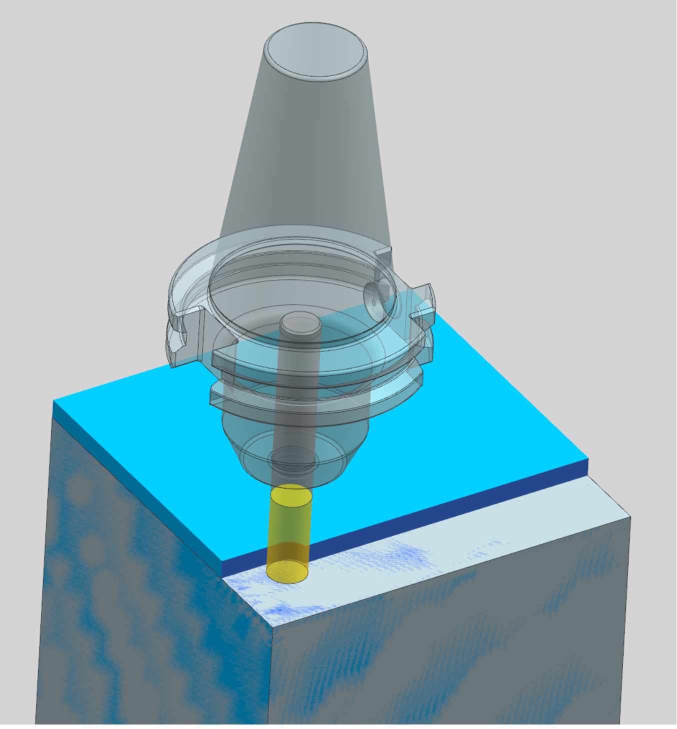


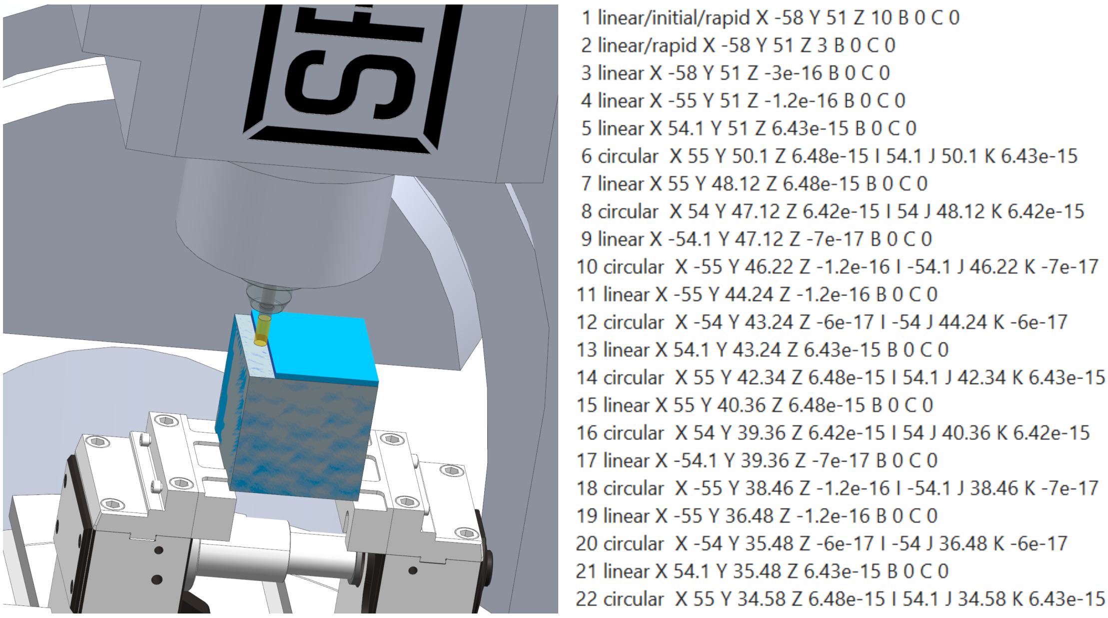
Figure 7.: Example of a CAM simulation without consideration of the control of the machine tool
Source: Own illustration.

---

[19] cf. Kief et al., (2017), p.650.

[20] cf. Oehler, (2016), pp.7-8.

Since this simulation is processed with the CLDATA format, any translation errors caused by the PP cannot be detected. Furthermore, errors that may occur during the generation of digital tools cannot be detected. For the tool, as shown in Figure 8 and 9, no CUTCOM - register (explained in more detail in Subsection 3.2.2) was specified for the cutting edge to be used. Many tool management systems evaluate "no entry" as value 0. The underlying problem here is that the PP uses the value 0 instead of, for example 1, to determine the cutting edge of the tool to be used. In this case, however, the value 0 sets the tool length to 0, as marked with a red circle in Figure 9b. Due to the fact that this is done by the PP, the simulation looks correct and error free, as shown in Figure 8. As shown in Figure 9, it would be fatal not to detect this error. Another problem with this method is the time calculation. No speed profiles are stored for the axes, so no exact calculation of the machining time can be made. A summary of the associated advantages and disadvantages of this method is shown in Table 1. [21,22]



```
linear/initial/rapid X -58 Y 51 Z 10 B 0 C 0
linear/rapid X -58 Y 51 Z 3 B 0 C 0
linear X -58 Y 51 Z -3e-16 B 0 C 0
linear X -55 Y 51 Z -1.2e-16 B 0 C 0
linear X 54.1 Y 51 Z 6.43e-15 B 0 C 0
circular  X 55 Y 50.1 Z 6.48e-15 I 54.1 J 50.1 K 6.43e-15
linear X 55 Y 48.12 Z 6.48e-15 B 0 C 0
circular  X 54 Y 47.12 Z 6.42e-15 I 54 J 48.12 K 6.42e-15
linear X -54.1 Y 47.12 Z -7e-17 B 0 C 0
circular  X -55 Y 46.22 Z -1.2e-16 I -54.1 J 46.22 K -7e-17
linear X -55 Y 44.24 Z -1.2e-16 B 0 C 0
circular  X -54 Y 43.24 Z -6e-17 I -54 J 44.24 K -6e-17
linear X 54.1 Y 43.24 Z 6.43e-15 B 0 C 0
circular  X 55 Y 42.34 Z 6.48e-15 I 54.1 J 42.34 K 6.43e-15
linear X 55 Y 40.36 Z 6.48e-15 B 0 C 0
circular  X 54 Y 39.36 Z 6.42e-15 I 54 J 40.36 K 6.42e-15
linear X -54.1 Y 39.36 Z -7e-17 B 0 C 0
circular  X -55 Y 38.46 Z -1.2e-16 I -54.1 J 38.46 K -7e-17
linear X -55 Y 36.48 Z -1.2e-16 B 0 C 0
circular  X -54 Y 35.48 Z -6e-17 I -54 J 36.48 K -6e-17
linear X 54.1 Y 35.48 Z 6.43e-15 B 0 C 0
circular  X 55 Y 34.58 Z 6.48e-15 I 54.1 J 34.58 K 6.43e-15
```

(a) Wrongly simulated movement of the machine tool
(b) Associated CLDATA code

Figure 8.: Example of a CAM simulation without consideration of the control of the machine tool
Source: Own illustration.

---

[21] cf. Kief et al., (2017), p.649.

[22] cf. Oehler, (2016), p.8.

Table 1.: Comparison of the advantages and disadvantages of a CAM simulation without consideration of the control

Source: Kief et al. (2017), p.650. and
Oehler (2016), p.8

Advantages	**Disadvantages**
Simulation is possible at an early stage	Potential incorrect translations of the PP are not recognized
Selection of a machine tool is not required	Kinematics of the machine tool are not taken into account
Selection of a clamping device is not required	Simulation of a classic NC code is not possible
	Incorrectly generated digital tools are not recognized

2.2.2.2. CAM Simulation with Emulated Control of the Machine Tool

Due to the potential error sources mentioned before, a CAM simulation without consideration of the control is insufficient. One way of eliminating these sources of error is to emulate the control of the respective machine tool during the CAM simulation. The basic difference between emulation and simulation is that an emulation only displays the target function correctly, but not the associated background processes. In this case the target function is the correct movement of the machine tool. In order to emulate the control of a machine tool during a CAM simulation, the respective machine tool and a corresponding PP must be selected before. After this, the CAM simulation is executed with the actual NC code, as shown in Figure 9. The main advantage with this method is that in the CAM simulation the machine tool moves just like the real machine tool. Possible errors in relation to an incorrect movement, which may be caused by the PP or by incorrectly digitalized tools, can be detected prematurely. Thus, a very reliable collision check is enabled with this method. The speed profiles of the axes of the machine tool are idealized in this method, which results in a reasonable time estimate. A list of all advantages and disadvantages is illustrated in Table 2. [23,24,25,26,27]

---

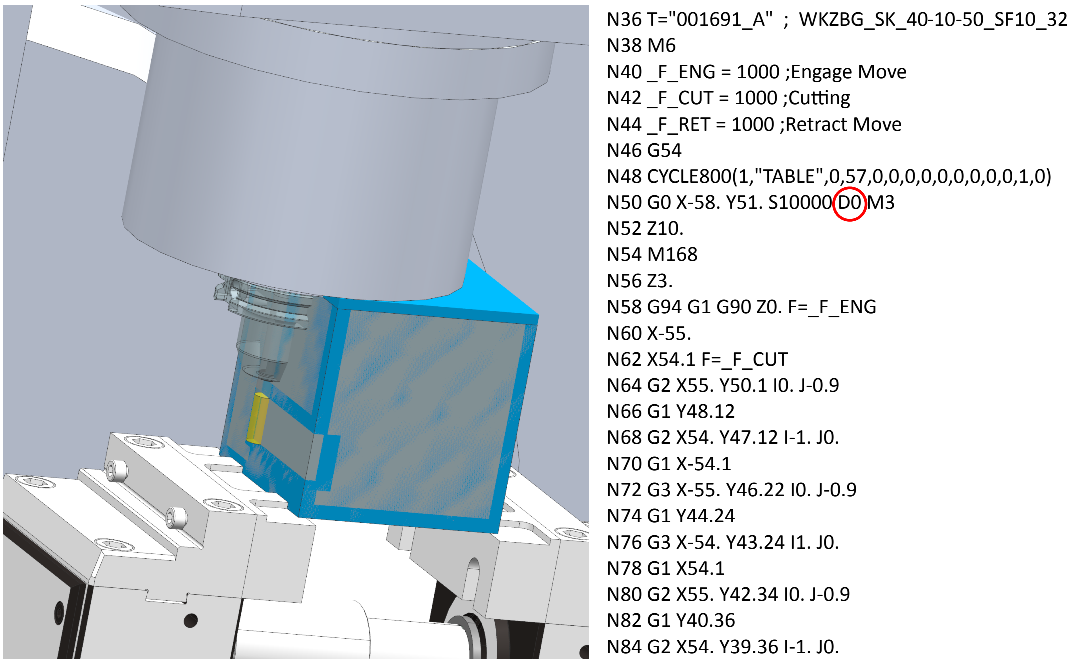
[23] cf. Hajicek, (2015).

[24] cf. Jedrzejewski / Kwasny, (2015).

[25] cf. Li et al., (2014).

[26] cf. Kief et al., (2017), p.650.

[27] cf. Oehler, (2016), pp.9-10.



```
N36 T="001691_A"  ;  WKZBG_SK_40-10-50_SF10_32
N38 M6
N40 _F_ENG = 1000 ;Engage Move
N42 _F_CUT = 1000 ;Cutting
N44 _F_RET = 1000 ;Retract Move
N46 G54
N48 CYCLE800(1,"TABLE",0,57,0,0,0,0,0,0,0,0,0,1,0)
N50 G0 X-58. Y51. S10000 D0 M3
N52 Z10.
N54 M168
N56 Z3.
N58 G94 G1 G90 Z0. F=_F_ENG
N60 X-55.
N62 X54.1 F=_F_CUT
N64 G2 X55. Y50.1 I0. J-0.9
N66 G1 Y48.12
N68 G2 X54. Y47.12 I-1. J0.
N70 G1 X-54.1
N72 G3 X-55. Y46.22 I0. J-0.9
N74 G1 Y44.24
N76 G3 X-54. Y43.24 I1. J0.
N78 G1 X54.1
N80 G2 X55. Y42.34 I0. J-0.9
N82 G1 Y40.36
N84 G2 X54. Y39.36 I-1. J0.
```

(a) Correct simulated movement of the machine tool

(b) Associated NC code with marked error

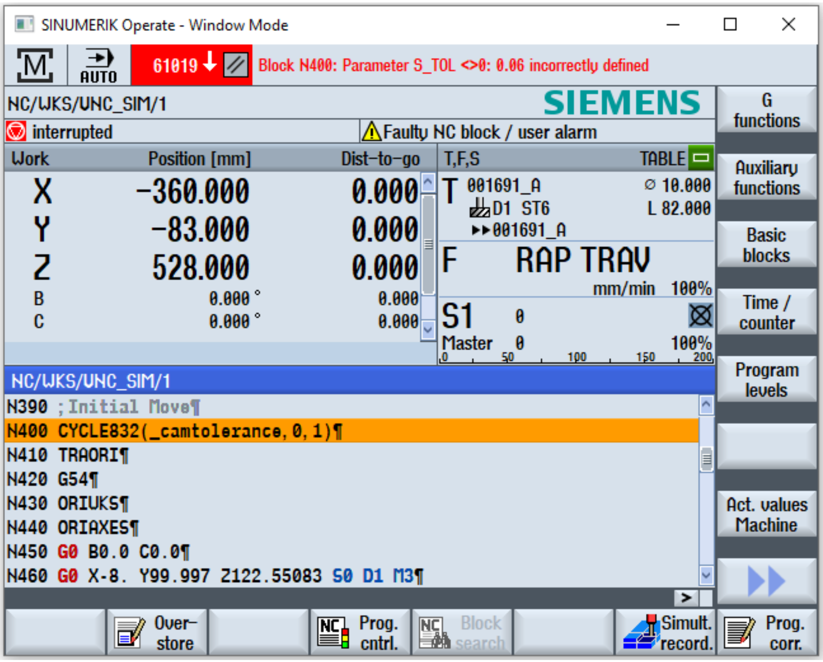
Figure 9.: Example of a CAM simulation with emulated control
Source: Own illustration.

Table 2.: Comparison of the advantages and disadvantages of an emulated control
Source: Kief et al. (2017), p.650. and
Oehler (2016), p.10

Advantages	**Disadvantages**
Different controls can be emulated within one platform	Control emulations are often insufficient for complex machines
Visualization of the machine tool and the entire manufacturing process is possible	Time calculation is based on idealized values and is not absolutely correct
Possible collisions can be detected	

2.2.2.3. CAM Simulation with Simulated Control of the Machine Tool

The fundamental problem with an emulated control is that the background processes of the real control are not taken into account. Therefore, it is not possible to check an NC code for correct syntax. Such an error will not result in a collision, but it can lead to a machine tool standstill and further to a loss of valuable time. A syntax error can occur despite a correct PP due to an unfortunate accumulation of CAM operations and it can therefore never be ruled out. To counteract this problem, there is the possibility of simulating a complete control of a machine tool in addition to the actual CAM simulation, as shown in Figure 10. In addition to the correct mapping of the background processes, a completely simulated control also results in the advantage of an accurately calculated time for the planned machining operations. Table 3 shows a summary of the advantages and disadvantages of this method. [28,29]



61019 Block N400: Parameter S_TOL <>0: 0.06 incorrectly defined

NC/WKS/UNC_SIM/1

interrupted

Faulty NC block / user alarm

```
Work   Position [mm]   Dist-to-go   T,F,S                        TABLE
X        -360.000        0.000      T  001691_A           ⌀ 10.000
Y         -83.000        0.000         D1  ST6              L 82.000
Z         528.000        0.000         ▸▸001691_A
B           0.000 °      0.000      F        RAP TRAV
C           0.000 °      0.000                     mm/min   100%
                                    S1       0
                                    Master   0                100%
                                    0    50    100    150    200
```

NC/WKS/UNC_SIM/1

```
N390 ;Initial Move¶
N400 CYCLE832(_camtolerance,0,1)¶
N410 TRAORI¶
N420 G54¶
N430 ORIUKS¶
N440 ORIAXES¶
N450 G0 B0.0 C0.0¶
N460 G0 X-8. Y99.997 Z122.55083 S0 D1 M3¶
```

Figure 10.: Syntax error, detected by a CAM simulation with simulated control
Source: Own illustration.

Table 3.: Comparison of the advantages and disadvantages of a simulated control
Source: Kief et al. (2017), p.650. and
Oehler (2016), p.12

Advantages	**Disadvantages**
Full functionality of the control	Very high computing power required
Identical operation and programming of real and digital machine tool	Performance usually worse than with control emulation
Correct processing time calculation	Complex installation

---

[28] cf. Kief et al., (2017), p.651.
[29] cf. Oehler, (2016), pp.11-12.

However, it is rather problematic that this method requires extremely high computing power and thus makes it difficult to work fluently. For this reason, it is possible to switch a simulated control to an emulated one and also to a CAM simulation without consideration of the control. The benefit of these possibilities is that more computing power is released and this enables a faster working process. Table 4 shows a summary of which CAM simulation method is used in which planning stage.

Table 4.: Different CAM simulation methods for different planning stages
Source: Own illustration.

CAM method	**Planning stage**	**Reason**
Without control	Individual operations are in the planning stage	In the planning stage of individual operations, the consideration of the control is only a hindrance.
Emulated control	Individual operations are ready to be tested	Whether the operations deliver the required result in terms of correct movement can only be tested with an emulated or simulated control. Due to performance reasons, an emulated control is used here.
Simulated control	The entire CAM program is ready to be tested	In order to check the NC code for correct syntax, the CAM program must be tested in the final state with a simulated control.

2.2.3. Different CAM Automation Methods

The working steps within a CAM software are mainly characterized by a manual selection of contours, areas and volumes as well as a subsequent linking of these elements with machining operations. In addition, a specific strategy must be selected for each of these operations and a set of tools and process parameters must be defined. Based on this information, the CAM software calculates a corresponding tool path for each operation. To facilitate the handling of these manual process steps, there is the possibility of a CAM automation. Essentially, this automation mechanism is based on the idea that similar components or similar component features can also be processed with similar machining operations. The possible automation methods are presented in the following subsections. [30,31]

---

[30] cf. Reinhart, (2017), p.344.

[31] cf. Woo et al., (2005).

2.2.3.1. Templates

The easiest way to support CAM programming is a template-based approach. Such templates include custom-fitted CAM setups, which include a selection of tools, clamping devices and operations, that have already been tested in combination. The benefit of this method heavily depends on the additional effort required to ensure that the new workpiece is processed correctly. One problem with the template-based method is the high effort necessary when templates have to be prepared for a wide variety of combinations of machine tools, clamping devices and tools. Table 5 shows the qualitative advantages and disadvantages of this method. [32]

Table 5.: Advantages and disadvantages of a template-based approach for CAM automation
Source: Reinhart (2017), p.344.

Advantages	**Disadvantages**
Easy to use	High maintenance effort

2.2.3.2. Feature-Macro Mapping

With the Feature-Macro Mapping (FMM) method, machining features such as drillings, pockets or grooves are assigned to a specific machining sequence by using macros. Before using this method, a processing sequence must first be defined in a database for all features. For example, a tool and a machining strategy must be assigned to each possible drilling type. If the CAD design of the drilling deviates from the definition in the database, the feature will not be recognized. Other problems arise from neutral data formats. If, for instance, a threaded hole, as also described in Subsection 2.2.1.1, is correctly designed in the CAD software, but saved in a neutral data format, data will be lost. Due to this data loss, the threaded hole is shown as a normal drilling and the feature is recognized as a normal drilling and thus would be manufactured incorrectly. The pros and cons of the FMM method are summarized in Table 6. [33]

---

[32] cf. Reinhart, (2017), p.344.

[33] cf. Reinhart, (2017), pp.344-345.

Table 6.: Advantages and disadvantages of a Feature-Macro Mapping method
Source: Reinhart (2017), p.344.

Advantages	**Disadvantages**
High productivity increase if the cooperation between CAD and CAM department is closely interlinked	Application for standard features only
	Data consistency from CAD to CAM required

2.2.3.3. Application Programming Interfaces

A further method of CAM automation are Application Programming Interfaces (API) extensions. These extensions usually have access to the CAD model, so they can perform any analysis regarding the geometry. At the same time, they can be integrated into the user interface of the CAM software and are able to create and parametrize machining operations independently. However, these extensive possibilities also involve a very high level of development and maintenance work and thus very high costs, so that automation via API is practically only implemented in special applications. The advantages and disadvantages of this method are summarized in Table 7. [34]

Table 7.: Advantages and disadvantages of Application Programming Interfaces
Source: Reinhart (2017), p.344.

Advantages	**Disadvantages**
Any automation mechanism can be implemented	Very high development effort, because often a new development
Possibility of integration in other systems	

---

[34] cf. Reinhart, (2017), p.346.

2.2.4. Automated CAM Documentation Method

Due to the fact that an NC code created by a CAM software often can be very extensive, it is advisable to create a documentation. In addition to the complexity and scope of such an NC code, another argument in favour of the necessity of a documentation is the fact that the CAM operator and the actual machine tool operator quite often are not the same person. Within Siemens NX, for example, there is the possibility of an automated CAM documentation method with the help of the "Shop Documentation" extension. The structure of the documentation can be adjusted as required. For example, the processing time is shown in the documentation for the respective tools as shown in Table 8, which allows the respective machine tool operator to draw conclusions about any service life of the tools. [35,36]

Table 8.: Example of a Shop Documentation
Source: Own illustration.

Index	Operation Name	Machine Mode	Tool Name	Tool Path Time
1	Mill Planar	Milling	T_001691_A	3.47 min
2	Spot Drilling	Drilling	T_002383_A	0.08 min
3	Drilling	Drilling	T_001728_A	0.27 min
4	Tapping	Drilling	T_001703_A	0.11 min

---

[35] cf. CAD CAM Engineering, (2014), Online-source [17.06.2020].

[36] cf. NX Manufacturing, (2019), Online-source [17.06.2020].

2.3. Data Management Methods

The basic difference in data management methods is whether a database is used or not. If data is stored in a database, a distinction can be made between Product Data Management (PDM) systems and PLM systems. PDM systems represent an integration platform for all tools to be used in the product development process, whereas PLM systems consider the entire product lifecycle. The major advantage of a PDM or PLM system is the possibility of an exact overview of where and how which files are referenced. This advantage particularly affects the use of a CAD and CAM software. All created files are referenced with each other and clearly identified by a consecutive identification number. Another advantage of these systems is the ability to customize the input masks. The specification of naming rules can be mentioned as an example. A very high implementation effort can be cited as a major disadvantage of these systems. [37,38,39,40]

2.4. Tool Management Software

In order to enable manufacturing planning when using a CAM software, the tools to be used have to be digitalized in addition to the actual machine tool. The different types of management of digital tools in tool databases can be classified as follows: [41]

- Tool management module dependent on CAM software
- Tool management software (TMS) independent from CAM software

The advantages and disadvantages of these variants are described in the following subsections.

---

[37] cf. Hofmann, (2017), p.153.

[38] cf. Scheidegger, (2016), p.198.

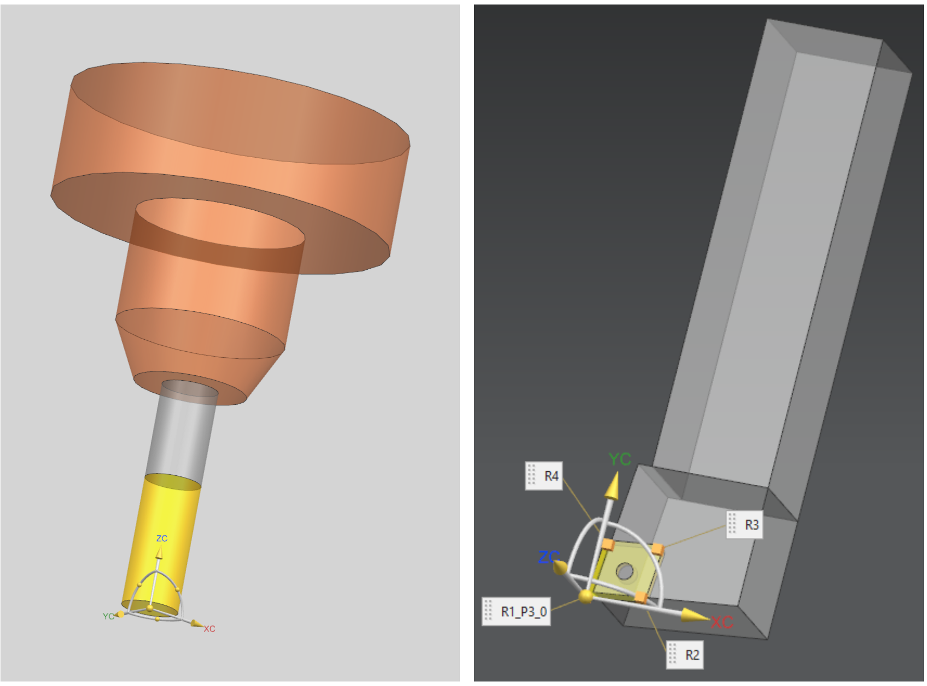
[39] cf. Siemens Digital Industries Software, (2020), Online-source [24.03.2020].

[40] cf. Bracht et al., (2017), pp.2-3.

[41] cf. Hofmann, (2017), p.64.

2.4.1. Tool Management Module Dependent on CAM Software

Every CAM software has a rather simple internal way of digitalizing the required tools. While such simple methods are sufficient for simple milling tools due to the rotational symmetry, their sufficiency is limited with turning tools, as shown in Figure 11. For the use of a CAM software under the condition that only the simplest milling tools are used and only one person works with the software, an internal tool management module can be used. However, if several people work with a CAM software or more complex tools are used, an independent TMS is advantageous, as explained below.



(a) Simple milling tool

(b) Simple turning tool

Figure 11.: Result of the internal tool management module from Siemens NX
Source: Own illustration.

2.4.2. Tool Management Software Independent from CAM Software

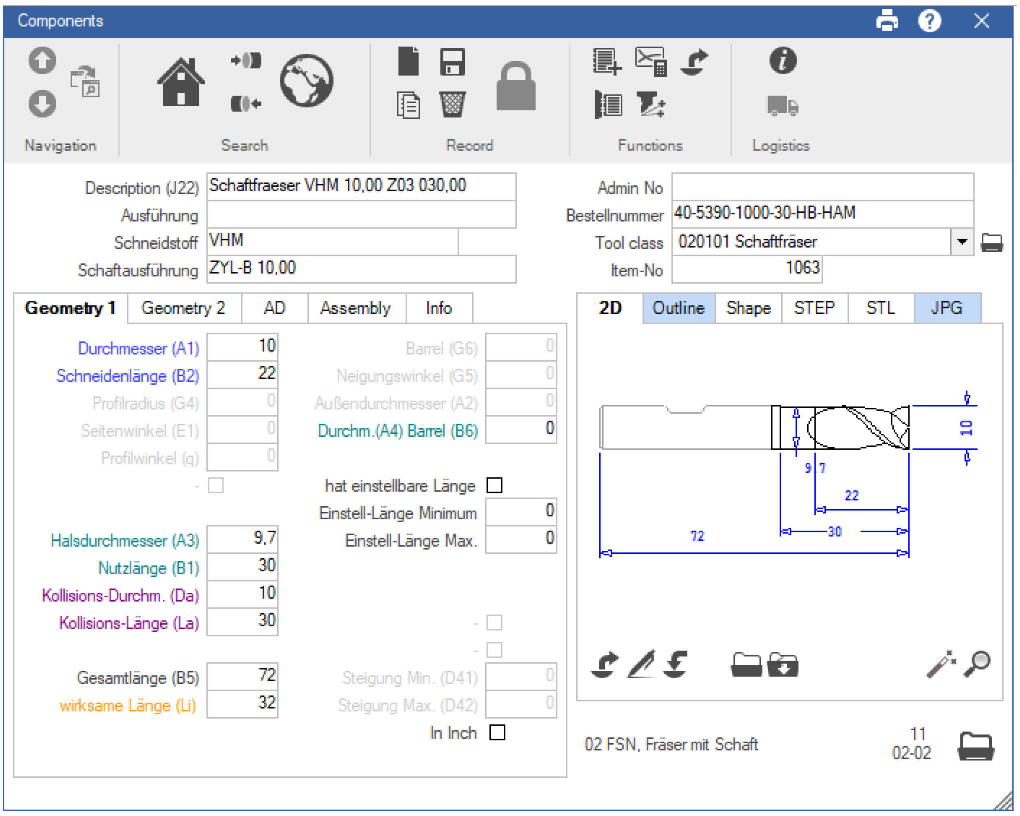
The fundamental difference between a TMS, which is independent from the CAM software and a dependent tool management module is the variety of setting and managing options. In addition, an independent TMS generally differentiates between individual components and complete tools. For this reason, the required components have to be created before a complete tool can be digitally assembled. This procedure offers the advantage that different components can be assembled into different complete tools without having to start from scratch each time. The way, these components should be set up is standardized in DIN 4003. It is advantageous if all components are constructed uniformly as described in the standard, but it is not absolutely necessary. [42,43,44,45]

2.4.2.1. Generation of the Required Tool Components

In order to generate a tool component, the respective TMS has to be given information about the geometry of the tool. There are basically two ways of providing information about tool components: With CAD data and without them. Input masks, as shown in Figure 12, enable the required data to be generated by entering different dimensions. However, the resulting data are not solid bodies as conventional CAD data, but metadata. These metadata are basically sufficient for the simulation if they correctly map the geometry of the tool. These input masks exist for most standard cutting tool components, but not for all components. Special cutting tool components must be mapped with CAD data. The structure of the tool components using CAD data always follows the same principle. A coordinate system has to be added to each component at the connection points. In principle, each non-cutting component has at least two connection points: One on the "machine tool side" and one on the "workpiece side". Cutting components only have one connection point on the "machine tool side". At these connection points a Mounting Coordinate System (MCS) and a Coordinate System Workpiece (CSW), must be inserted in the CAD data. Figure 13 serves as an example. [46,47,48]

---

[42] cf. DIN 4003-1, (2017).
[43] cf. Stoldt et al., (2018).
[44] cf. Schaupp et al., (2017).
[45] cf. Teti / D'Addona, (2011).
[46] cf. Botkinaa et al., (2018).
[47] cf. Brenner et al., (2017).
[48] cf. Maier et al., (2018).



Description (J22)	Schaftfraeser VHM 10,00 Z03 030,00
Ausführung	
Schneidstoff	VHM
Schaftausführung	ZYL-B 10,00
Admin No	
Bestellnummer	40-5390-1000-30-HB-HAM
Tool class	020101 Schaftfräser
Item-No	1063

Durchmesser (A1)	10	Barrel (G6)	0
Schneidenlänge (B2)	22	Neigungswinkel (G5)	0
Profilradius (G4)	0	Außendurchmesser (A2)	0
Seitenwinkel (E1)	0	Durchm.(A4) Barrel (B6)	0
Profilwinkel (q)	0		
-	☐	hat einstellbare Länge	☐
		Einstell-Länge Minimum	0
Halsdurchmesser (A3)	9,7	Einstell-Länge Max.	0
Nutzlänge (B1)	30		
Kollisions-Durchm. (Da)	10		
Kollisions-Länge (La)	30	-	☐
		-	☐
Gesamtlänge (B5)	72	Steigung Min. (D41)	0
wirksame Länge (Li)	32	Steigung Max. (D42)	0
		In Inch	☐

02 FSN, Fräser mit Schaft

11
02-02

Figure 12.: Example of an input mask for creating a milling cutter
Source: Own illustration.

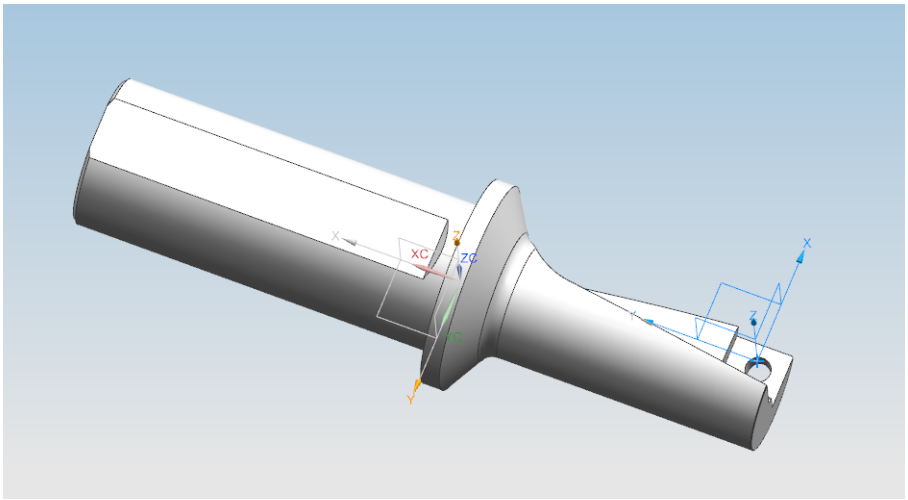


Figure 13.: Example of a turning insert holder
Source: Own illustration.

After adding the coordinate systems, the component must be classified within the TMS. Firstly, the component has to be assigned to a class. Afterwards further attributes have to be added to the component. So-called connection codes are important here, which enable the subsequent digital assembly into a complete tool. These connection codes are assigned to the coordinate systems MCS and CSW, which enable a search function within the TMS. With this method, only suitable components are shown when a complete tool is assembled. This is described in more detail in Subsection 2.4.2.2. Other attributes, which have to be assigned are component dependent. For example, milling cutters need the attributes "Peripheral Effective Cutting Edge Count" and "Face Effective Cutting Edge Count" for the calculation of any cutting values in the CAM software. If these values are missing, an error message will be issued in the CAM software. Furthermore, it is advisable to fill in the attribute of the material of the cutting component to enable the cutting values to be calculated automatically, as explained in Subsection 2.4.3.3. Since this digitalization process is very time-consuming, many tool manufacturers offer the opportunity to buy digital tool catalogs, which contain the data of digital tool components that can be loaded into a TMS. The problem, however, is that many manufacturers use different standards and therefore the components often do not match and need to be reworked. Furthermore, it cannot be guaranteed that these components have the correct geometry. For these reasons, the application of this method has to be questioned. [49,50,51,52,53,54]

2.4.2.2. Digital Assembly of Complete Tools

Before being able to use digital complete tools in a CAM software, tool components must be assembled into complete tools. It does not matter at which end the assembly process starts, but it is advisable to always assemble a tool in sequence. If, for example, the assembly process is started with a milling cutter that has a connection code of "ZYL0910xxxx", only a component with a suitable connection code can then be added. During the assembly process, the coordinate systems MCS and CSW of the respective counterparts are overlaid. If these coordinate systems are defined incorrectly, the components will be assembled incorrectly. In the case of rotationally symmetrical tools, only the axis of rotation has to match. With turning tools, however, the coordinate systems must be correct in all axes. After the assembly process, the respective components have to be

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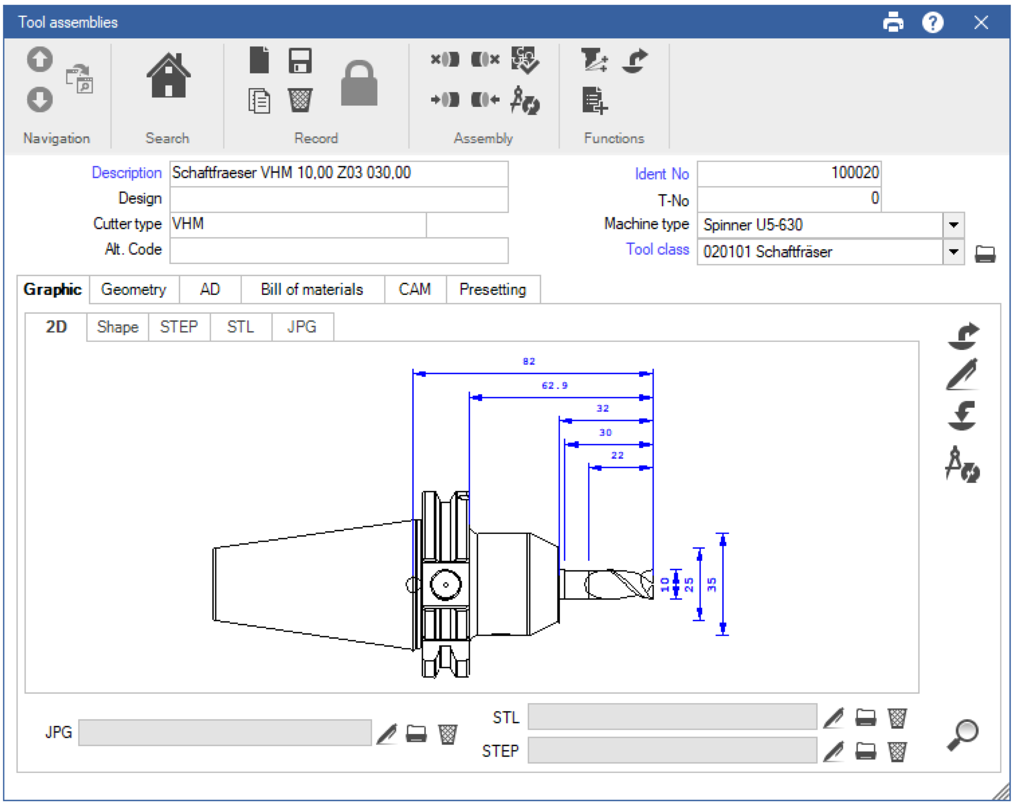
[49] cf. Hofmann, (2017), pp.59-83.
[50] cf. DIN 4003-1, (2017).
[51] cf. Meseguer / Gonzalez, (2008).
[52] cf. Raschinger et al., (2016).
[53] cf. Rao et al., (2011).
[54] cf. Heeschen et al., (2015).

classified based on the attributes "cutting", "non-cutting" and "tool-holder" to enable a precise collision analysis. The complete tool must then also be classified. Figure 14 shows a complete tool, which is classified as an endmill. The complete tool illustrated is constructed without a pull stud. The use of pull studs in digital tools is viewed as controversial, since a wide variety of designs are possible. Due to the fact that pull studs are not relevant with regard to collision checks and the fact that planning without them significantly reduces the digitalization effort, they are often omitted within the whole planning task and are assembled just before the physical tool is inserted into the machine tool. [55,56,57,58,59,60]



Tool assemblies

Description Schaftfraeser VHM 10,00 Z03 030,00
Design
Cutter type VHM
Alt. Code
Ident No 100020
T-No 0
Machine type Spinner U5-630
Tool class 020101 Schaftfräser

Figure 14.: Example of a complete tool classified as an endmill without pull stud
Source: Own illustration.

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[55] cf. DIN 4003-1, (2017).
[56] cf. Botkinaa et al., (2018).
[57] cf. Brenner et al., (2017).
[58] cf. Maier et al., (2018).
[59] cf. Bosch / Metternich, (2018).
[60] cf. Haffer et al., (2018).

When considering the assembly process of a complete tool in a TMS, certain attributes are inherited from the cutting component. This includes, for example, attributes such as the diameter, the possible length of cut, the collision length or the tool material. These attributes vary depending on the type of component. Furthermore, the attribute "machine type" can be defined for a complete tool. With this attribute the complete tool can be assigned to a specific machine tool. This has the advantage that when searching for tools for a specific machine tool, only suitable ones are displayed.

2.4.3. Management of Machining Data

In addition to the geometry parameters of tools, machining data can also be managed in a TMS. A distinction can be made between three different variants: [61,62]

- Machining data related to a tool component
- Machining data related to a complete tool
- Machining data saved in a Machining Data Library

2.4.3.1. Machining Data Related to a Tool Component

The simplest form of managing machining data is to assign them to a tool component. In addition to the typical values such as "cutting speed", "cutting feed", "cutting width" and "cutting depth", engage strategies can also be defined. The advantage of machining data that relate to a component is that they are inherited to a complete tool when it is assembled. The problem with this method is that the machining data may have to be varied in relation to the composition of the complete tool. However, since these machining data are inherited from the cutting component to the complete tool, the values may be incorrect. [63,64]

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[61] cf. Siemens, (2016), Online-source [23.07.2020].

[62] cf. Siemens PLM Software, (2015), Online-source [23.07.2020].

[63] cf. NC matic, (2017), Online-source [23.07.2020].

[64] cf. Zhang / Wang, (2016).

2.4.3.2. Machining Data Related to a Complete Tool

To compensate the aforementioned problem, the machining data can also be assigned to a complete tool. Basically, this is identical to the process described before. Generally, the machining data can be precisely defined and assigned to a complete tool using this method. The problem with this method is that there is more than one set of valid machining data for a complete tool available. Due to the fact that not only one material is always processed with a complete tool, the machining data may have to be varied. Another cutting method with different cutting depths can also be used, for which the machining data have to be adjusted. [65,66]

2.4.3.3. Machining Data Saved in a Machining Data Library

In order to save machining data independently of a tool, there is the option of saving them into a Machining Data Library (MDL). The following parameters can be assigned to a combination of cutting speed and feed: [67]

- Machine tool
- Workpiece material
- Cutting depth
- Tool material
- Cutting method
- Tool diameter
- Cutting width

If the MDL is then filled with sufficient values, a suitable combination of cutting speed and feed is then transferred in relation to the other parameters. If there are not enough values stored in the MDL, the values of the cutting speed and feed will be interpolated. Another problem with the use of an MDL is that a composition of a complete tool is not considered. [68,69,70]

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[65] cf. NC matic, (2017), Online-source [23.07.2020].

[66] cf. Zhang / Wang, (2016).

[67] cf. Siemens, (2016), Online-source [23.07.2020].

[68] cf. Peng et al., (2015).

[69] cf. Gittler et al., (2019).

[70] cf. Tseng et al., (2019).

2.4.3.4. Acquisition of Suitable Machining Data

To make sure that cutting values can be loaded regardless of the storage type, they must be saved correctly beforehand. Table 9 shows the possible characteristics of the data sources. It should be emphasized that, despite the most reliable variant of the "Shop floor experience", machining data often have to be tested in order to obtain a correct value. It must also be mentioned that any kind of database for cutting values represents an abstraction, since a certain number of parameters are used here. [71,72,73,74,75]

Table 9.: Characteristics of data sources of machining data
Source: Peng et al. (2015).

Data source	**Characteristics**
Machining data handbooks	Systematization; data richness; easy collection
Software simulation	Economical; data needs to be validated by experiments before application
Laboratory experiments	Lower reliability than shop floor experience but better than simulation
Shop floor experience	Data scattering; good reliability

2.4.3.5. Determination of Economical Cutting Conditions

The determination of economically optimal cutting conditions is of particular importance, as these have to be adapted depending on the application due to different combinations of machine tools, tools and workers and the associated cost factors. With regard to all cutting data, the wear effect of the cutting speed is the highest in contrast to the feed rate and cutting depth. For this reason, the depth of cut and the feed rate can be maximized and the cutting speed must be optimized with regard to tool life. [76,77]

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[71] cf. Haffer et al., (2017), pp.356-357.
[72] cf. Gomeringer et al., (2014), p.18.
[73] cf. Schmid et al., (2008), p.246.
[74] cf. Peng et al., (2015).
[75] cf. Manufacturing Automation Laboratories, (2017).
[76] cf. VDI 3321, (1994).
[77] cf. Klocke, (2018), pp.441-456.

A distinction can be made between a cost-optimized and a time-optimized cutting speed. With regard to these two possibilities, an optimization regarding costs will be preferable under normal circumstances. Nevertheless, in the event of delivery bottlenecks or general time pressure, an optimization with regard to time can also take place. In order to be able to carry out these optimizations, a tool-life-cutting-speed-test with at least two different cutting speeds within the technical cutting value limits must be carried out beforehand. The values obtained can then be plotted twice logarithmically and connected by a straight line (Taylor tool life line), as illustrated in Figure 15. [78,79,80]

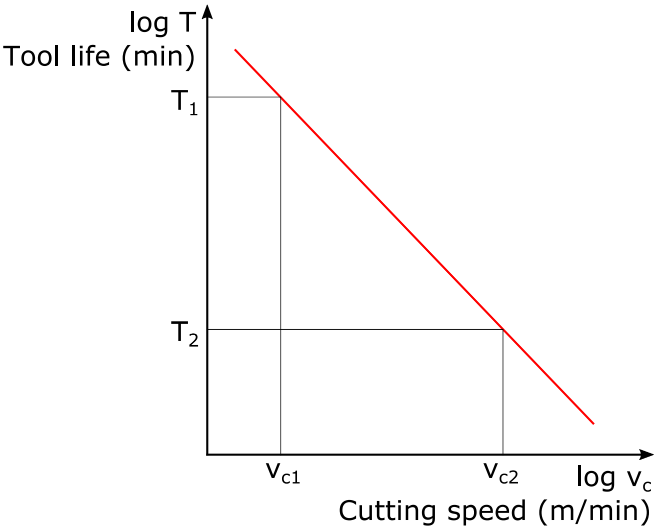

Figure 15.: Taylor tool life line
Source: Own illustration.

The Taylor tool life line obtained can be described by equations 2.1 and 2.2. Within these equations, T corresponds to the tool life, k to the slope of the tool life line, v_c to the cutting speed and C_T is the theoretical tool life at a cutting speed of one meter per minute.

$$log(T) = k \cdot log(v_c) + log(C_T) \tag{2.1}$$

$$T = C_T \cdot v_c^k \tag{2.2}$$

---

[78] cf. VDI 3321, (1994).

[79] cf. Klocke, (2018), pp.441-456.

[80] cf. Black / Kohser, (2019), pp.421-425.

The cost-optimized cutting speed $v_{c_{oc}}$ is then calculated using Equation 2.3 and the time-optimized cutting speed $v_{c_{ot}}$ is calculated using Equation 2.4. Within these equations, $t_{exchange}$ corresponds to the tool change time, K_{Tool} the tool costs per tool life and K_{ML} are the machine tool and labor costs per time.

$$v_{c_{oc}} = \sqrt[k]{-(k+1) \cdot \frac{t_{exchange} + \frac{K_{Tool}}{K_{ML}}}{C_T}} \tag{2.3}$$

$$v_{c_{ot}} = \sqrt[k]{-(k+1) \cdot \frac{t_{exchange}}{C_T}} \tag{2.4}$$

2.4.4. Simulation of the Machining Process

The CAM simulation methods described in the previous subsections mainly describe the geometric consideration of the machining process, such as the movement of the individual axes. However, the full use of the available cutting performance is often prevented by chatter vibrations which can lead to reduced tool life, poor surface quality, high noise emissions and even damage to the machine tool. A machining process is therefore considered to be unstable as soon as chatter vibrations have started. Stable areas of the machining process are indicated in so-called stability lobes. Basically, the generation of stability lobes has been established, in which the maximum cutting depth is specified as a function of the spindle speed, as shown as an example in Figure 16. In addition to the experimental method of creating such a stability lobe, it can also be generated by a simulation. Within such a simulation, a previously generated NC code or a CAM program can be adapted to maximum chatter-free conditions in terms of cutting width, cutting depth, cutting speed and cutting feed. To enable this simulation, the dynamics of the machine tool must be measured using a tap test (impulse hammer test) so that the required Frequency Response Function (FRF) can be determined. Furthermore, cutting coefficients for the used tools and the material of the workpiece must be defined. [81]

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[81] cf. Brecher / Weck, (2017), pp.597-613.

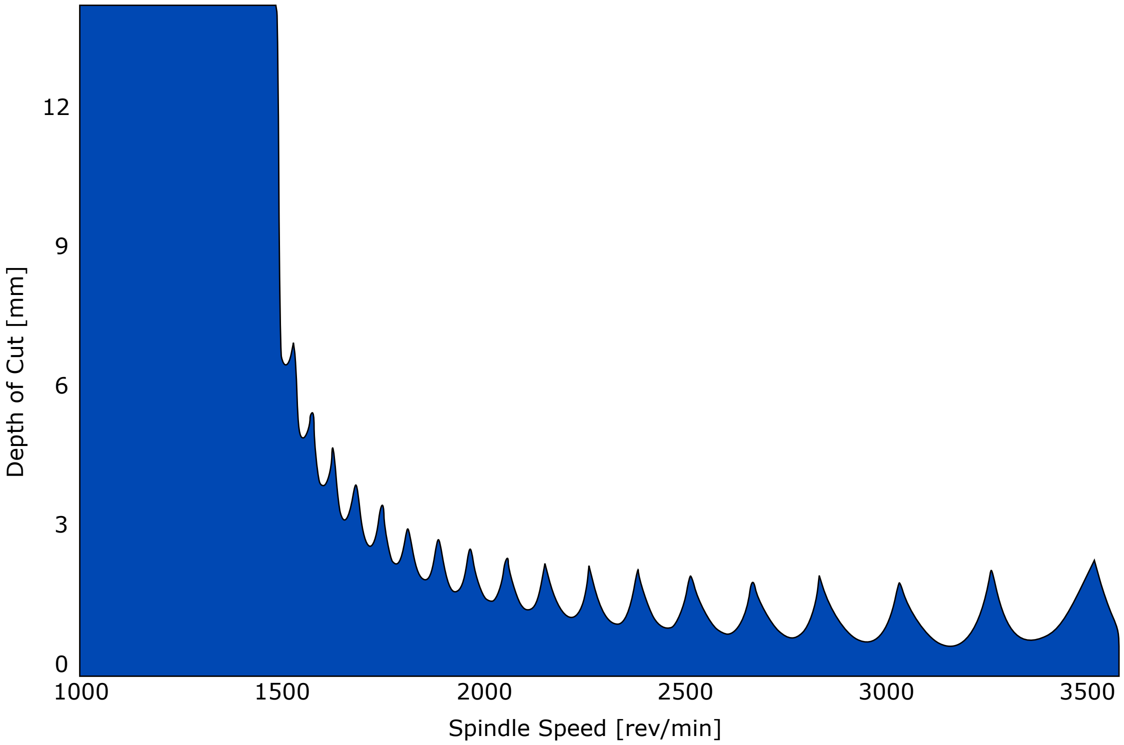

Figure 16.: Stability lobe for Sandvik 10.0mm 4-flute cutter, 0.20mm cutting width
Source: Manufacturing Automation Laboratories (2017).

The limiting factor for the machining process is the most flexible part, which, within milling machine tools, is the spindle-toolholder-tool system. Generally, all three coordinate directions should be considered, but with milling cutters, the flexibility in the Z-direction is significantly lower (stiffness is much higher) than in the other two coordinate directions and can therefore be ignored. For this reason, the FRF must be determined in the X- and Y-direction. If a heavy face milling operation is used, however, the Z-direction must also be determined. If a thin-walled workpiece is to be machined, the FRF function must be determined for the workpiece in all directions as well. If this is not the case, the FRF for the workpiece can be neglected, since the flexibility is lower than that of the spindle-toolholder-tool system. [82,83,84,85]

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[82] cf. Binder, (2018).

[83] cf. Manufacturing Automation Laboratories, (2017).

[84] cf. Altintas, (2016).

[85] cf. Erkorkmaz et al., (2006).

Depending on the system used, the cutting coefficients have to be determined manually or can be inherited from the CAM setup. In general, the properties (diameter, helix and rake angles, number of teeth etc.) of each cutter have to be determined. Next to these geometrical parameters, some information of the associated operation (milling mode, spindle direction, etc.) must be provided and a material must be assigned to the workpiece. After this assignment, the simulation can be started and a stability lobe, as shown in Figure 16, can be created. [86,87,88,89]

In the course of this work, the software NPRO, which is an application for Siemens NX and the software CUTPRO, which is a standalone-software, have been tested. In addition to optimization with regard to chatter, both software products offer further optimization options such as optimization with regard to cutting forces. The difference between these products is that NPRO can be used within the CAM software. The functionality of NPRO can be classified as excellent, the suitability for lot size 1 production, however, as good under certain conditions. The problem is that a FRF must be determined for every new complete tool. Within lot size 1 production, new tool types will often occur. Each tool would have to be assembled physically before the simulation process to determine the FRF. This hinders productivity within the lot size 1 production to a very high degree. For this reason, this method is not considered any further in this thesis.

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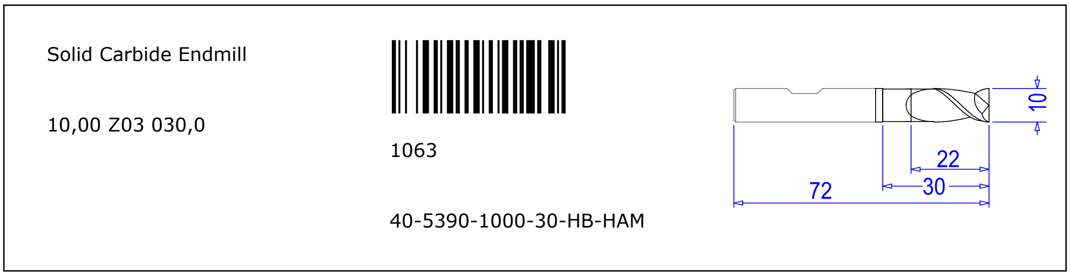
[86] cf. Manufacturing Automation Laboratories, (2017).
[87] cf. Altintas et al., (2014).
[88] cf. Kilic / Altintas, (2016).
[89] cf. Estman et al., (2014).

2.5. Physical Tool Management

Before the machining on the real machine tool can be started, the tools to be used must be set up. As with the digital counterparts, the physical complete tools have to be assembled from the respective components. Then the complete tools have to be measured and the measured values must be transferred to the machine tool.

2.5.1. Tool Set-up List

Depending on the possibilities of the TMS used, a "bill of materials" for the complete tool can be generated. This functionality can be used to create a complete component list of all complete tools of the entire CAM program. An example of such a set-up list is shown in Figure 17. In addition to the list of components, dimensions relevant to the assembly process are also shown. The meaning of the barcode next to the components of the set-up list is explained in Subsection 2.5.2.



Solid Carbide Endmill

10,00 Z03 030,0

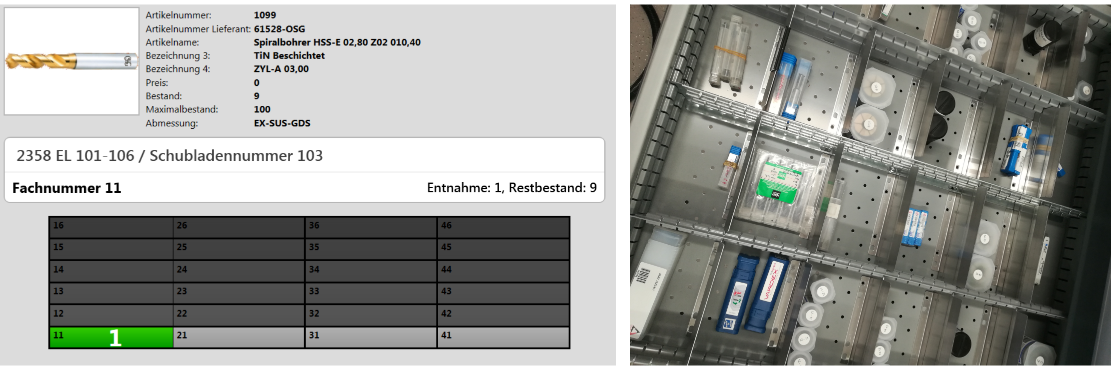
1063

40-5390-1000-30-HB-HAM

Figure 17.: Excerpt from a tool set-up list
Source: Schmid / Pichler (2020).

2.5.2. Tool Dispensing System

In addition to the possibility of managing the digital components and complete tools, there is also the possibility of managing the physical counterparts by using a tool dispensing system (TDS), which can be linked to a TMS. This connection enables that the storage locations of the physical components and complete tools can be assigned to the digital counterparts within the TMS. If a tool list is generated, as shown in Figure 17, barcodes are assigned to each component. These barcodes can then be scanned by the TDS and after this scanning process, the software of the TDS shows the exact position of the desired component, as shown in Figure 18a. The major problem with this system is the fact that the components must always be assigned correctly. Moreover, the components used must be properly booked in again, after every disassembly process. In order to limit the sources of error, this TDS is locked and can only be opened by authorized employees at a registration at the beginning. The respective drawer only opens after the barcode has been scanned, as shown in Figure 18b. After all required components have been taken from the TDS, they can be assembled into complete tools using the set-up information on the tool list. [90,91,92]



Artikelnummer: **1099**
Artikelnummer Lieferant: **61528-OSG**
Artikelname: **Spiralbohrer HSS-E 02,80 Z02 010,40**
Bezeichnung 3: **TiN Beschichtet**
Bezeichnung 4: **ZYL-A 03,00**
Preis: **0**
Bestand: **9**
Maximalbestand: **100**
Abmessung: **EX-SUS-GDS**

2358 EL 101-106 / Schubladennummer 103

Fachnummer 11
Entnahme: 1, Restbestand: 9

16	26	36	46
15	25	35	45
14	24	34	44
13	23	33	43
12	22	32	42
11 1	21	31	41

(a) Position specification by the tool dispensing system

(b) Matching position in the tool dispensing system

Figure 18.: Localized position of the required tool component
Source: Own illustration.

2.5.3. Tool Measurement

Each complete tool must be measured before it can be used in a machine tool. The values to be measured differ fundamentally, depending on whether the tool is used in a lathe machine tool or in a milling machine tool. For example, tools for a milling machine tool have to be measured in length and diameter, as shown in Figure 19. Tools for a lathe machine tool have to be measured in two, or in all three coordinate directions, depending on the kinematics. Special tools are not considered in this classification. [93,94]

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[90] cf. Schaupp et al., (2016).
[91] cf. Mansour Fallah et al., (2019).
[92] cf. Reinhart, (2017), pp.335-337.
[93] cf. Hofmann, (2017), pp.84-89.
[94] cf. Scheidegger, (2016), pp.329-347.

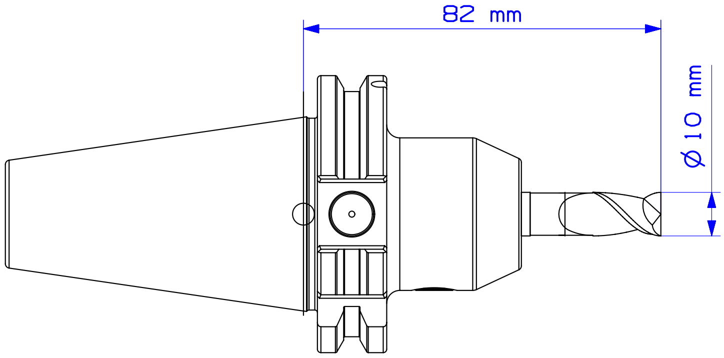

Figure 19.: Values of a complete tool to be measured, using the example of a milling cutter
Source: Own illustration.

Generally, the measurement methods can be classified into two categories:

- Measurement inside the machine tool: touch probe or laser-system
- Measurement outside the machine tool: presetting and measuring machine

The main advantage of the measuring method outside the machine tool is that the machine tool itself can be used for production simultaneously. The disadvantage of this method is that the measured values have to be transferred to the machine tool and then assigned to the correct complete physical tool. If there is a confusion between the measured values and the tool, the machine tool can be seriously damaged by a possible collision. Table 10 shows the basic advantages and disadvantages of the measurement methods by "Touch probe", "Laser-system" and "Presetting and measuring machine".

Table 10.: Comparison of presetting and measuring machine, touch probe and laser-system
🔴 (not sufficient), 🟡 (sufficient), 🟢 (excellent)
Source: Scheidegger (2016), p.123.

Measurement task	**Presetting and measuring machine**	**Touch probe**	**Laser-system**
Length measurement	🟢	🟢	🟢
Radius measurement	🟢	🟡	🟢
Tool presetting	🟢	🔴	🔴
Concentricity control	🟡	🔴	🟢
Dynamic spindle drift	🔴	🔴	🟢
Thermal machine drift	🔴	🟡	🟢
Shaft-Fracture control	🔴	🟢	🟢
Single cutting edge control	🟡	🟡	🟢
Edge shape control	🟡	🔴	🟢
Wear compensation	🔴	🔴	🟢
Investment costs	high	low	moderate

This comparison shows that the laser-system is the best system in terms of quantity of functions. However, the presetting is impossible, because it is an internal system. Despite the functions that a laser-system has to offer, the presetting and measuring machine is the preferred choice, because of the high amount of time saved during the measuring process. With regard to an absolute ideal solution, a combination of a presetting and measuring machine and a laser-system would be desirable. [95]

A fundamental problem of digital tools is the fact that their physical counterparts have to be assembled identically, otherwise there is a risk of collision on the machine tool. In principle, a set-up instruction is also supplied with a set-up list, but whether the tools are ultimately assembled in this way can never be guaranteed. Since all tools have to be measured after the physical assembly process, a test loop can be installed. As shown in Figure 20, valid ranges can be specified, for example, for the clamping position of a milling cutter within an associated holder. This valid range can be taken over by the presetting and measuring machine. If the physical complete tool is not within the area, the presetting and measuring machine will display a warning message. [96,97]

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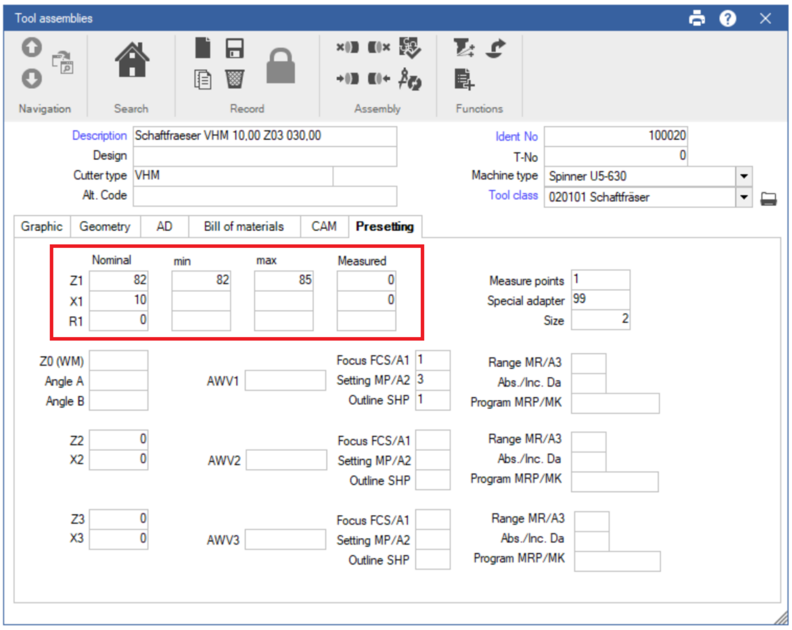
[95] cf. Scheidegger, (2016), pp.329-347.
[96] cf. Kief et al., (2017), pp.518-520.
[97] cf. Schreiber / Zimmermann, (2011), pp.199-201.



Description Schaftfraeser VHM 10,00 Z03 030,00
Design
Cutter type VHM
Alt. Code
Ident No 100020
T-No 0
Machine type Spinner U5-630
Tool class 020101 Schaftfräser

	Nominal	min	max	Measured
Z1	82	82	85	0
X1	10			0
R1	0			

Measure points 1
Special adapter 99
Size 2

Z0 (WM)
Angle A
Angle B
AWV1
Focus FCS/A1 1
Setting MP/A2 3
Outline SHP 1
Range MR/A3
Abs./Inc. Da
Program MRP/MK

Z2 0
X2 0
AWV2
Focus FCS/A1
Setting MP/A2
Outline SHP
Range MR/A3
Abs./Inc. Da
Program MRP/MK

Z3 0
X3 0
AWV3
Focus FCS/A1
Setting MP/A2
Outline SHP
Range MR/A3
Abs./Inc. Da
Program MRP/MK

Figure 20.: Valid ranges of the length of a complete tool
Source: Own illustration.

A very high number of errors can be excluded by the method presented above. However, the system can still be bypassed. For example, a complete tool can be assembled with an incorrect variation of components. Since only the length and diameter of the complete tool are measured, the measured values can be in a valid range despite the wrong components. This can lead a to significant difference in relation to the respective contour of the tool, which can also lead to a collision. To avoid this error, there is the possibility of adding specific check marks of the contour. The problem here, however, is that these check marks have to be added manually for each individual complete tool. [98]

2.5.4. Data Transfer Methods of a Presetting and Measuring Machine to a Machine Tool

If a complete tool has been successfully measured on a presetting and measuring machine, the measured values must be transferred to the desired machine tool. The following subsections explain the main advantages and disadvantages of the possible methods. [99,100]

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[98] cf. Zoller, (2016), Online-source [23.07.2020].

[99] cf. Scheidegger, (2016), p.331.

[100] cf. Hofmann, (2017), pp.89-91.

2.5.4.1. Manual Data Input

The simplest form of data transfer is the manual entry of the measured data into the internal tool database of the machine tool. The measured values are often transferred by using post-its. However, this type of data transfer is the most unreliable. The post-its can be lost or a typing error can occur when the values are entered manually. As mentioned in previous sections, a wrong value of the tools in the internal tool database can lead to a collision of the machine tool. [101,102]

2.5.4.2. Self-adhesive Labels

The measured values can also be transferred by using a self-adhesive label on each complete tool as shown in Figure 21. A distinction must be made between a data trasfer with and without Quick Response (QR) code. The method without QR-code differs from the post-it method, as mentioned in the previous subsection, only in that as the measured values are not written down by hand and therefore potential errors are only partially reduced. When data are transferred using QR-code, the measured values are managed within the system and can be read by the machine tool using a suitable reading device, as shown in Figure 21b. With this method, the labels can either be glued directly onto the tool or, as shown in Figure 21a, onto a plastic clip, (shown in yellow) which can then be attached to the tool. This plastic clip has to be removed when the tool is set up in the machine tool. The disadvantage of this method is that the measured value is no longer connected to the tool. However, if cooling lubricant was used in the machine tool, the label would be damaged and needed to be replaced after some weeks. The associated data loss is the fundamental disadvantage of this method. The basic functionality of the data transfer from the reader to the control of the machine tool is equivalent to that of a standard PC keyboard. The reader can be connected to the control of a machine tool via USB and transfer the data as if a PC keyboard was connected. This enables a very simple retrofitting. [103,104,105]

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[101] cf. Reinhart, (2017), pp.337-338.
[102] cf. Kief et al., (2017), pp.518-520.
[103] cf. Zoller, (2018c), Online-source [27.03.2020].
[104] cf. Scheidegger, (2016), p.331.
[105] cf. Hofmann, (2017), pp.89-91.

(a) Data transfer via Quick Response code

(b) Data import process

Figure 21.: Data transfer via self-adhesive label
Source: Zoller (2018c), Online-source [27.03.2020].

2.5.4.3. Radio-Frequency Identification

Another way of transferring data is through using a Radio-Frequency Identification (RFID) data carrier which is attached to every complete tool. This data carrier is written with the required data by the presetting and measuring machine after the measurement process and can then be read-in by the reading device of the machine tool. The advantages and disadvantages of this method are listed in the following Table 11. [106,107,108,109,110]

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[106] cf. Emanuele et al., (2015).
[107] cf. Chang et al., (2006).
[108] cf. Liukkonen, (2014).
[109] cf. Zoller, (2018b), Online-source [27.03.2020].
[110] cf. IT Production, (2014), Online-source [27.03.2020].

Table 11.: Advantages and disadvantages of the data transfer method via RFID
Source: Hofmann (2017), pp.89-91.

Advantages	**Disadvantages**
Each complete tool can be clearly identified via the RFID data carrier.	The complete tools may have to be balanced because the glued-in data carrier creates an imbalance.
The data transfer process is very reliable.	This method is very expensive because a writing station must be installed on each presetting and measuring machine and a reading station on each machine tool.
	Despite the very high investment costs, not all sources of error are eliminated.
	If the complete tool is disassembled, values such as tool life are lost.

2.5.4.4. Direct Numerical Control

The Direct Numerical Control (DNC) transfer method enables the measured values to be transferred from the presetting and measuring machine to the machine tool directly. By doing so, the measured values are converted into a machine tool readable program by an internal PP of the presetting and measuring machine. This PP must be adjusted according to the control of the machine tool. This program is then saved to a folder shared on the network, which is integrated into the machine tool. In addition to the transfer method via the network, this can also be done via USB or also via RS232 on older machine tools. After calling and executing the program on the machine tool, the measured values are saved in the internal tool database of the machine tool. The tools can then be physically set up. The advantages and disadvantages of this method are listed in Table 12. [111,112,113,114,115]

---

[111] cf. Xiang et al., (2013).
[112] cf. Wang et al., (2012).
[113] cf. Huang / Yan, (2011).
[114] cf. Xun et al., (2012).
[115] cf. Zoller, (2018a), Online-source [23.07.2020].

Table 12.: Advantages and disadvantages of the data transmission method via DNC
Source: Hofmann (2017), pp.89-91.

Advantages	**Disadvantages**
Very cost-effective since no hardware is required.	Measured values are not physically linked to the complete tool as with the RFID method, which creates a risk of confusion.
	Higher effort due to the necessary additional identification of the tools.

2.5.4.5. Reduction of the Error Rate Through Combination of Measurement Systems

None of the transfer methods listed allows absolute freedom from errors. However, since the set-up process is to be classified as critical, the error rate can be reduced by a combination of different systems. For example, internal measurement methods can be used as a further test loop. As already shown in Table 10, the laser-system has a very high functionality. This functionality can be used to further reduce the set-up error rate. For example, the laser-system can be used to compare the actual length with the transferred value after the physical set-up process. This would guarantee that the tool length and diameter would match, but the contour of the tool could still be flawed. [116,117]

2.6. Computerized Numerical Control

CNC controls are a further development of the NC technology. NC controls are generally controls with very limited or no storage options. Program data are read in using a punched tape reader and then processed by the NC control. For these reasons, pure NC controls are hardly used any more and the term NC nowadays corresponds to a general description of the entire CNC technology. They differ from NC controls in the sense that CNC controls are built using microprocessors. This means that much more computing power and memory is available. This allows larger amounts of data to be processed quickly and, for example, several axes to be controlled simultaneously. Furthermore, a graphic operating system can be used to create and adapt programs directly on the control. [118]

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[116] cf. MARPOSS, (2019), Online-source [17.06.2020].

[117] cf. MAV, (2014), Online-source [17.06.2020].

[118] cf. Scheidegger, (2016), pp.159-161.

3. Elaboration of a Suitable CAD-CAM-CNC Process Chain

Within this chapter, the selected process chain and its implementation sequence is described in detail. The selection of the different systems is described at the beginning of this chapter, followed by the actual implementation of these systems. An implementation strategy of the whole process chain is then presented at the end of this chapter.

3.1. Selected Systems

An optimal process chain generally valid for SMEs does not exist, as this is dependent on the area of application of the respective company. For this reason, the area of application of the fictitious SME under consideration is defined as a contract manufacturer (lot size 1). The requirements for the process chain are therefore the ability to quickly program the machine tools and to deal with the many associated set-up processes. The selection process is fundamentally influenced by the fact that SMEs usually do not have as many resources as LEs. Nevertheless, the final process chain has to be also as error-free and effective as possible. In order to develop a process chain that meets these requirements, the components are selected according to the characteristics of having a lower implementation effort with similar effectiveness. Despite this compromise, a future expansion should still be possible with manageable effort. The different systems described below show a chosen optimum considered for this situation.

3.1.1. CAD-CAM Coupling Variant

An **integrated CAD-CAM system**, as explained in Subsection 2.2.1.2, has been selected to be examined in this thesis. The reasons why an integrated system has to be preferred over a coupled one are, in addition to the obvious advantages, that an integrated system can also be operated as a coupled one, but not vice versa. Furthermore, the implementation effort of an integrated system is identical to that of a coupled one.

3.1.2. CAM Simulation Method

In order to be able to carry out the optimal CAM simulation in lot size 1 manufacturing, the **CAM simulation with simulated control of the machine tool**, as described in Subsection 2.2.2.3, has been selected. The main reason why this method has been chosen is that a CAM simulation without consideration of the control of the machine tool is not sufficient, especially for 5-axis simultaneous machining.

3.1.3. CAM Automation Method

The CAM automation methods FMM and API have not been chosen, as they are simply not suitable for lot size 1 manufacturing, due to an extremely high implementation effort, as explained in Subsection 2.2.3.2 and 2.2.3.3. For this reason, the method via **Templates** has been chosen for further examination.

3.1.4. Data Management Method

Within this thesis a **PLM system** has been chosen instead of a PDM system, because every functionality of a PDM system is covered by a PLM system. The implementation effort of a complete PLM system can be classified as very high. For this reason, only the PDM module of the PLM system is used (and licensed) at the beginning of the implementation, but the possibility of expanding to a complete PLM system is not excluded.

3.1.5. Tool Management Software

The type of a **TMS independent from a CAM software** is used in this thesis. The reason for this decision next to the wide variety of additional functions without any extra effort in the application, is the fact that the system is independent from the CAM software. If the CAM software was subsequently changed, the previously generated tool data could still be used.

3.1.6. Method for Managing Machining Data

The management of machining data is generally associated with a lot of effort with regard to lot size 1 production, as there are endless combinations of suitable values. The method of **machining data saved in an MDL** proved to be the most suitable, since not all entries have to be created again in the case of a new combination, which would result in less effort.

3.1.7. Tool Measurement Method

Lot size 1 production involves a very high number of set-up processes. Due to the set-up processes, the machine tool down times do not have to be further increased by internally measuring the tools. For this reason, the method of measuring tools externally on a **presetting and measuring machine** has been chosen.

3.1.8. Transfer of the Measured Values from the Presetting and Measuring Machine to the Machine Tool

Based on the fact that lot size 1 production involves a very high number of tool set-up processes, only a limited number of tool components will probably be available in SMEs, due to financial reasons. For this reason, complete tools will increasingly be disassembled to use the respective components for other complete tools that are required. In this case, data of the remaining tool life are lost and the possibilities that are given by the data transfer method using RFID, can therefore not be fully used. For this reason, this method is not recommended in this case. Although the data transfer method via DNC is rather low in cost and reliable, it has the disadvantage that the physically complete tool is not connected to the measured value. The effect of this lack of connection is that the respective measured tool must be set-up immediately on the machine tool after each measuring process, otherwise there is a risk of confusion. Since the manual methods are very unreliable, only the data transfer method using QR-code remains after the elimination process. This code can be applied using self-adhesive labels or laser engravings. The laser engraving method, offers the possibility of storing tool life, which cannot be used properly either. For this reason, the transfer method **QR-code with self-adhesive labels** has been chosen. Additional units, such as a laser system, has not been chosen for the selected process chain, as this would be associated with very high investment costs and the additional functionality is rated as not necessary.

3.1.9. Software and Hardware Used

The relevant software and hardware used for this thesis are listed in Tables 13 and 14. It should be mentioned that the respective software versions are updated regularly. The software versions listed in the two tables are those used at the end of the work on this thesis.

Table 13.: Software used within this thesis
Source: Own illustration.

Software type	**Software**	**Version**
CAD/CAM software	Siemens NX	12
PLM software	Siemens Teamcenter	11
PLM transfer software	Shopfloor Connect for Teamcenter	2020.3
Tool management software	Siemens Manufacturing Resource Library	11.5.0.7
Tool management software	WinTool	2019.1
Machining data software	Siemens Machining Data Library	11.5.0.7
Post-processor software	Post Builder	12.0.2
Machine tool control emulation software	Machine Configurator	1.0.0.1027
Machine tool control simulation software	VNCKView	4.7.4

Table 14.: Hardware used within this thesis
Source: Own illustration.

Hardware type	**Hardware**	**OS version**
Milling machine tool	SPINNER U5-630 - Sinumerik 840D sl	Operate 4.8
Presetting and measuring machine	Zoller Venturion 450	Pilot 4.0
Tool dispensing system	Toolbase EL-6 Professional	ATMS 2018

3.2. Implementation of the Process Chain

The systems selected in Section 3.1 are used and linked with each other. The required connections of the individual subsystems are shown, through the entire process chain, which is illustrated in Figure 22 and explained in Table 15. The sequence of the individual stations is presented, based on a complete run of a product, from design to manufacturing. How the individual systems are linked is described in the following subsections.

Table 15.: Data transfer steps in the CAD-CAM-CNC process chain as shown in Figure 22
Source: Own illustration.

Nr.	**Data to be transferred**	**Explanation**
1	CAD Data	CAD data is transferred and saved to the PLM software after the design process has been finished
2	CAD Data	CAD data is then loaded from the PLM software with an integrated CAM software
3	Digitally Complete Tools	Digitally complete tools are loaded from the TMS into the CAM software
4	CAM Data & Machine Specific NC code incl. documentation	CAM data, NC code and documentation are saved in the PLM software after CAM planning
5	Tool - List	A list of the selected complete tools is transferred back to the TMS after CAM planning
6	Tool - Component - List	The previously transferred list of complete tools is separated into its components and a list of the required tool components is created
7	Tool - List for Measuring	The list of complete tools is transferred to the presetting and measuring machine, together with the settings related to the measurement process
8	Physically Complete Tools	After the assembly process, the physically complete tools are transferred to the presetting and measuring machine for measurement
9	Measuring Values of Physically Complete Tools	After the measuring process, the measured values are transferred to the machine tool
10	Physically Complete Tools	The complete physical tools are also transferred to the machine tool for the set-up process

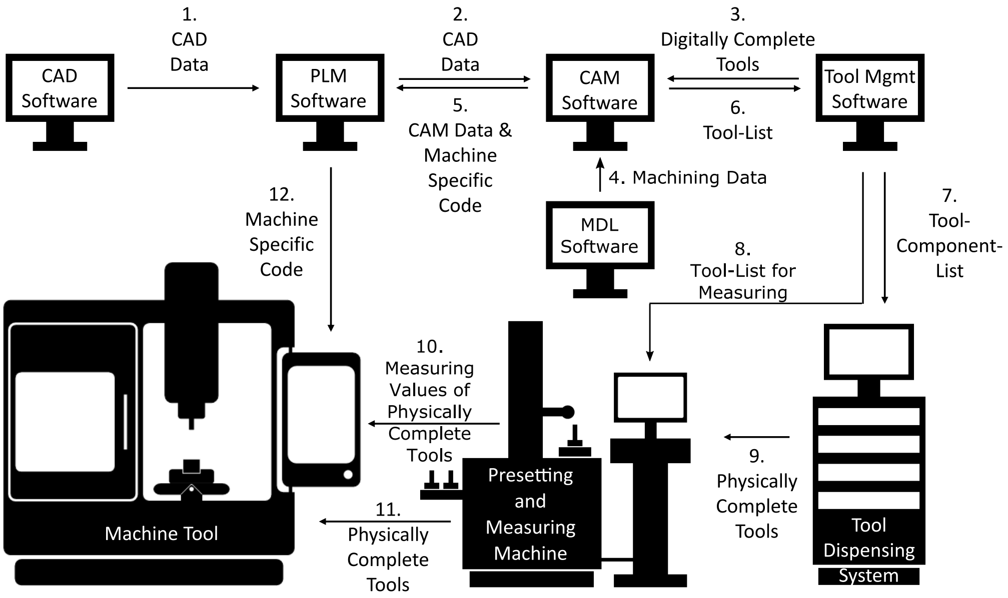


Figure 22.: CAD - CAM - CNC - process chain in the smartfactory@tugraz
Source: Schmid / Pichler (2020).

3.2.1. Connection of the CAD-CAM Software with the PLM Software

In the course of this thesis, completely new system installations have been carried out. In order to enable a data transfer as shown in Figure 23, the systems have to be set-up very specifically, which has been done together with experts from Siemens. The connection process of the individual elements is established by a specific file (*.dat) which contains all the necessary paths. Every client that has to be integrated into the system network must contain a reference to this file in addition to the correct installation.

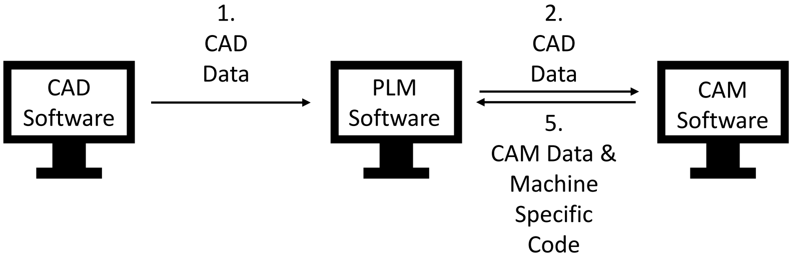


Figure 23.: Data transfer from CAD and CAM software to PLM software
Source: Schmid / Pichler (2020).

3.2.2. Connection of the Tool Management Software with the CAM Software

The most important factor of a TMS is a reliable data transfer from the TMS to the CAM software, as shown in Figure 24. It is essential that all values of all those variables, which are then used by a PP to generate NC code, are transferred correctly. The variables "Tool Name", "Tool Number", "Adjust Register" and "Cutcom Register" are named as examples of very critical variables because they are used to call the physical tools at the machine tool and to assign the compensation lengths.

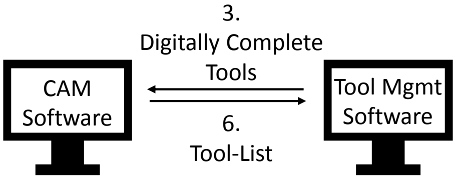


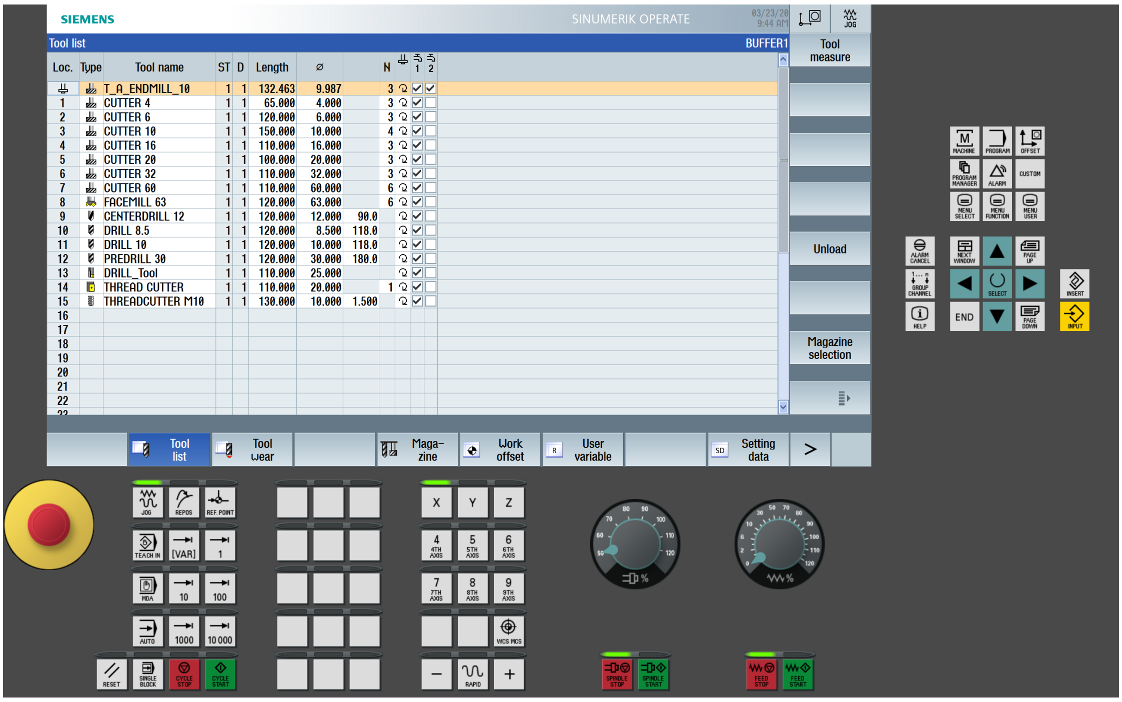
Figure 24.: Data transfer from tool management software to CAM software
Source: Schmid / Pichler (2020).

Figures 25 and 26 show the internal tool management of a milling and lathe machine tool with a Sinumerik 840D sl control. In order to change a tool on the machine tool, it has to be called by name followed by the command M6, as shown in Table 16. Then the associated correction lengths must be loaded, which is done with command D and the associated "Cutting edge number". Within a milling machine tool there is almost always only one possibility of a length, which can be loaded with command D1. However, if tools have two cutting edges, such as tool Nr. 5, as shown in Figure 26, the associated lengths must be loaded with command D2.

These variables must be reproduced by the TMS and the CAM software. The problem is, that these variables are addressed differently by each machine tool - control and TMS manufacturer, which can be seen in Table 17. Here, the interface of the TMS has to be adapted to the CAM software, PP and machine tool used, which is explained below.

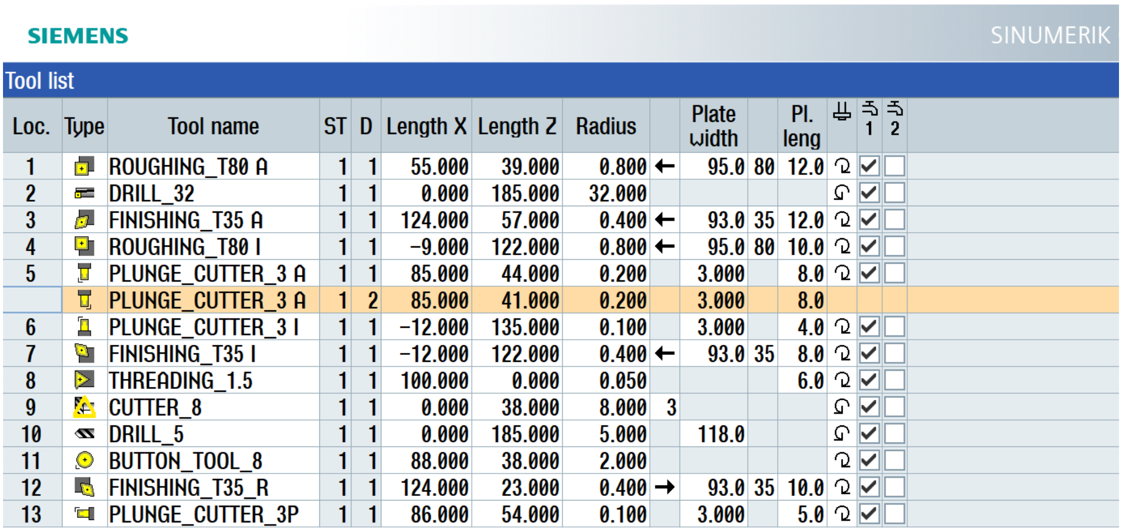
Table 16.: Example of a tool change on a machine tool with a Sinumerik control
Source: Own illustration.

Qualitative example:	**Real example:**
T="**Tool Name**" M6 D(**Cutting edge number**)	T="PLUNGE_CUTTER_3 A" (Figure 26) M6 D2



Loc.	Type	Tool name	ST	D	Length	⌀		N		1	2
		T_A_ENDMILL_10	1	1	132.463	9.987		3	↻	☑	☑
1		CUTTER 4	1	1	65.000	4.000		3	↻	☑	☐
2		CUTTER 6	1	1	120.000	6.000		3	↻	☑	☐
3		CUTTER 10	1	1	150.000	10.000		4	↻	☑	☐
4		CUTTER 16	1	1	110.000	16.000		3	↻	☑	☐
5		CUTTER 20	1	1	100.000	20.000		3	↻	☑	☐
6		CUTTER 32	1	1	110.000	32.000		3	↻	☑	☐
7		CUTTER 60	1	1	110.000	60.000		6	↻	☑	☐
8		FACEMILL 63	1	1	120.000	63.000		6	↻	☑	☐
9		CENTERDRILL 12	1	1	120.000	12.000	90.0		↻	☑	☐
10		DRILL 8.5	1	1	120.000	8.500	118.0		↻	☑	☐
11		DRILL 10	1	1	120.000	10.000	118.0		↻	☑	☐
12		PREDRILL 30	1	1	120.000	30.000	180.0		↻	☑	☐
13		DRILL_Tool	1	1	110.000	25.000			↻	☑	☐
14		THREAD CUTTER	1	1	110.000	20.000		1	↻	☑	☐
15		THREADCUTTER M10	1	1	130.000	10.000	1.500		↻	☑	☐
16											
17											
18											
19											
20											
21											
22											

Figure 25.: Internal tool management of a milling machine tool with a Sinumerik 840D sl control
Source: Own illustration.



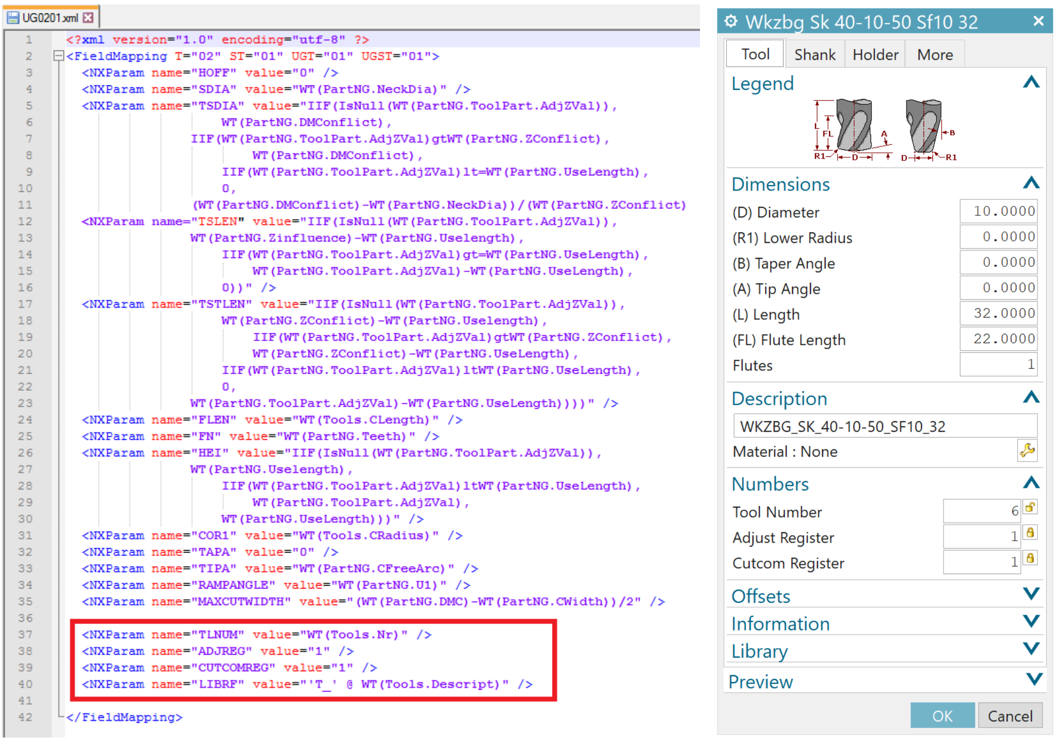
Loc.	Type	Tool name	ST	D	Length X	Length Z	Radius		Plate width		Pl. leng		1	2
1		ROUGHING_T80 A	1	1	55.000	39.000	0.800	←	95.0	80	12.0	↻	☑	☐
2		DRILL_32	1	1	0.000	185.000	32.000					↺	☑	☐
3		FINISHING_T35 A	1	1	124.000	57.000	0.400	←	93.0	35	12.0	↻	☑	☐
4		ROUGHING_T80 I	1	1	-9.000	122.000	0.800	←	95.0	80	10.0	↻	☑	☐
5		PLUNGE_CUTTER_3 A	1	1	85.000	44.000	0.200		3.000		8.0	↻	☑	☐
		PLUNGE_CUTTER_3 A	1	2	85.000	41.000	0.200		3.000		8.0			
6		PLUNGE_CUTTER_3 I	1	1	-12.000	135.000	0.100		3.000		4.0	↻	☑	☐
7		FINISHING_T35 I	1	1	-12.000	122.000	0.400	←	93.0	35	8.0	↻	☑	☐
8		THREADING_1.5	1	1	100.000	0.000	0.050				6.0	↻	☑	☐
9		CUTTER_8	1	1	0.000	38.000	8.000	3				↺	☑	☐
10		DRILL_5	1	1	0.000	185.000	5.000		118.0			↺	☑	☐
11		BUTTON_TOOL_8	1	1	88.000	38.000	2.000					↻	☑	☐
12		FINISHING_T35_R	1	1	124.000	23.000	0.400	→	93.0	35	10.0	↻	☑	☐
13		PLUNGE_CUTTER_3P	1	1	86.000	54.000	0.100		3.000		5.0	↻	☑	☐

Figure 26.: Internal tool management of a lathe machine tool with a Sinumerik 840D sl control
Source: Own illustration.

Table 17.: Different definitions of important variables
Source: Own illustration.

SINUMERIK	Siemens NX CAM	TMS WinTool	Definition
Location	Tool Number	TLNUM	Magazine / location number
Tool Name	Tool Name	LIBREF	Tool Name
D	Cutcom Register or Adjust Register	CUTCOMREG or ADJREG	Cutting edge number

To enable a correct data transfer between the individual systems, the respective variables have to be linked to each other. This can be done with the TMS WinTool via XML files. Here, as shown in Figure 27 for milling tools, value 1 is always communicated for "Cutcom Register" and "Adjust Register". If more complicated tools with several cutting edges are used, value 1 must be replaced in the XML file by CUTCOMREG or ADJREG, as shown in Table 17.



```
<?xml version="1.0" encoding="utf-8" ?>
<FieldMapping T="02" ST="01" UGT="01" UGST="01">
  <NXParam name="HOFF" value="0" />
  <NXParam name="SDIA" value="WT(PartNG.NeckDia)" />
  <NXParam name="TSDIA" value="IIF(IsNull(WT(PartNG.ToolPart.AdjZVal)),
                    WT(PartNG.DMConflict),
                IIF(WT(PartNG.ToolPart.AdjZVal)gtWT(PartNG.ZConflict),
                        WT(PartNG.DMConflict),
                    IIF(WT(PartNG.ToolPart.AdjZVal)lt=WT(PartNG.UseLength),
                    0,
                (WT(PartNG.DMConflict)-WT(PartNG.NeckDia))/(WT(PartNG.ZConflict)
  <NXParam name="TSLEN" value="IIF(IsNull(WT(PartNG.ToolPart.AdjZVal)),
                WT(PartNG.Zinfluence)-WT(PartNG.Uselength),
                    IIF(WT(PartNG.ToolPart.AdjZVal)gt=WT(PartNG.UseLength),
                        WT(PartNG.ToolPart.AdjZVal)-WT(PartNG.UseLength),
                    0))" />
  <NXParam name="TSTLEN" value="IIF(IsNull(WT(PartNG.ToolPart.AdjZVal)),
                    WT(PartNG.ZConflict)-WT(PartNG.Uselength),
                        IIF(WT(PartNG.ToolPart.AdjZVal)gtWT(PartNG.ZConflict),
                        WT(PartNG.ZConflict)-WT(PartNG.UseLength),
                    IIF(WT(PartNG.ToolPart.AdjZVal)ltWT(PartNG.UseLength),
                    0,
                WT(PartNG.ToolPart.AdjZVal)-WT(PartNG.UseLength))))" />
  <NXParam name="FLEN" value="WT(Tools.CLength)" />
  <NXParam name="FN" value="WT(PartNG.Teeth)" />
  <NXParam name="HEI" value="IIF(IsNull(WT(PartNG.ToolPart.AdjZVal)),
                WT(PartNG.Uselength),
                    IIF(WT(PartNG.ToolPart.AdjZVal)ltWT(PartNG.UseLength),
                        WT(PartNG.ToolPart.AdjZVal),
                    WT(PartNG.UseLength)))" />
  <NXParam name="COR1" value="WT(Tools.CRadius)" />
  <NXParam name="TAPA" value="0" />
  <NXParam name="TIPA" value="WT(PartNG.CFreeArc)" />
  <NXParam name="RAMPANGLE" value="WT(PartNG.U1)" />
  <NXParam name="MAXCUTWIDTH" value="(WT(PartNG.DMC)-WT(PartNG.CWidth))/2" />

  <NXParam name="TLNUM" value="WT(Tools.Nr)" />
  <NXParam name="ADJREG" value="1" />
  <NXParam name="CUTCOMREG" value="1" />
  <NXParam name="LIBRF" value="'T_' @ WT(Tools.Descript)" />

</FieldMapping>
```

(a) XML file to control data transfer

Wkzbg Sk 40-10-50 Sf10 32

(D) Diameter	10.0000
(R1) Lower Radius	0.0000
(B) Taper Angle	0.0000
(A) Tip Angle	0.0000
(L) Length	32.0000
(FL) Flute Length	22.0000
Flutes	1

WKZBG_SK_40-10-50_SF10_32
Material : None

Tool Number	6
Adjust Register	1
Cutcom Register	1

(b) Effect of the XML file

Figure 27.: Example of an XML file to control the data transfer from tool management software to CAM system for milling tools
Source: Own illustration.

3.2.3. Connection of the Tool Management Software with the Tool Dispensing System

To enable the communication between the TDS and the TMS, as shown in Figure 28, both systems have to be connected. The communication between the two systems takes place via a folder shared in the network. The TDS stores the stocks and locations of the respective components in that folder so that the TMS can use them to generate a tool set-up list, as shown in Figure 17. This connection has been established by experts from the industry and is thus not further discussed.

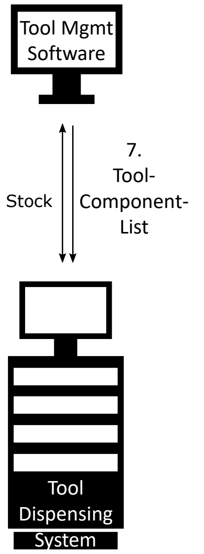


Figure 28.: Data transfer from tool management software to tool dispensing system
Source: Schmid / Pichler (2020).

3.2.4. Connection of the Tool Management Software with the Presetting and Measuring Machine

The communication of the TMS and the presetting and measuring machine, as shown in Figure 29, also takes place via a folder shared in the network. The TMS has a ready-made interface which can address the presetting and measuring machine used. Here, data sets are created which can then be loaded from the presetting and measuring machine. The setting for this is done via an XML file. This connection has also been set-up by an expert and will not be considered further in the following work.

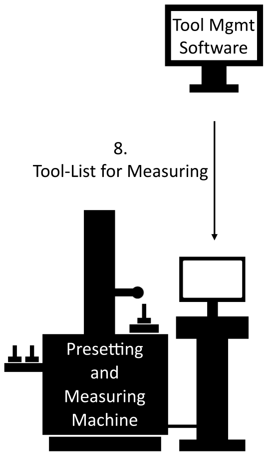


Figure 29.: Data transfer from tool management software to presetting and measuring machine
Source: Schmid / Pichler (2020).

3.2.5. Connection of the Presetting and Measuring Machine with the Machine Tool

After a measuring process at the presetting and measuring machine, the measured values are linked to a QR-code, which is printed on a label. This QR-code can be read in by the reading device on the machine tool, which is connected via USB and acts like a PC-Keyboard. In order to enable a correct transfer, the data output of the presetting and measuring machine must be adapted to the control of the desired machine tool. To do this, a suitable template can be selected from a number of ready-made templates. The data transfer method, as shown qualitatively in Figure 30, has been set-up together with an expert from the industry.

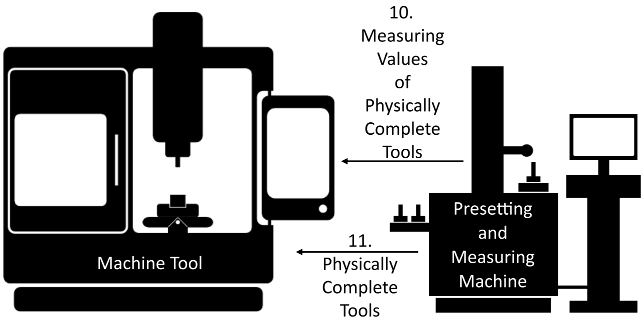


Figure 30.: Data transfer from presetting and measuring machine to machine tool
Source: Schmid / Pichler (2020).

3.2.6. Connection of the PLM Software with the Machine Tool

In order to connect the PLM software Siemens Teamcenter with the machine tool, as qualitatively shown in Figure 31, the add-on SFC is used. This add-on is a browser-based application, which enables a simplified access to the released manufacturing data. After the manual entry of the article number of the component to be manufactured all associated information can be displayed on a suitable device (Tablet, PC, etc.). How an NC code or an associated documentation is named, for example, is irrelevant since all networked and released files are recognized. Once production data has been found it can be viewed and the NC code then can be transferred. The NC code is then copied to a network drive, from which it can be loaded into the control of the machine tool. This connection has also been set-up by an expert and will not be considered further in the following work.

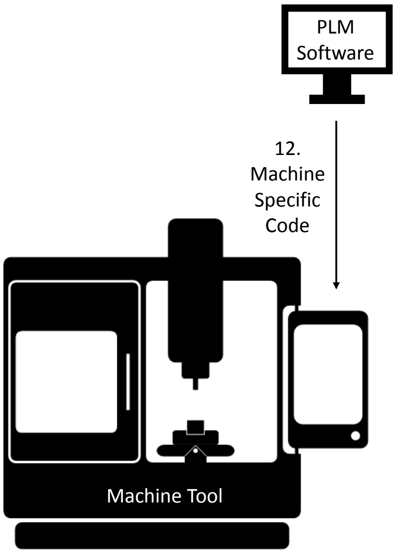


Figure 31.: Data transfer from PLM software to the machine tool
Source: Schmid / Pichler (2020).

3.3. Process Chain Implementation Maturity Model

In this section, a maturity model of the CAD-CAM-CNC process chain, described above, is presented to explain an advantageous implementation sequence for an exemplarily selected initial situation.

A maturity model comprises a series of maturity levels for a class of objects and thereby describes an anticipated, desired or typical development path of these objects in successive, discrete ranks, starting at an initial stage and following it up to complete maturity. The determination of individual maturity levels of objects takes place by means of specifically defined assessment methods, which suggestions for improvement for the determined actual situation can be derived from.

Within this thesis, the procedure model for the generation of maturity levels according to Becker et al. (2009) [1] is used. The most important aspects of this procedure model are that the generation of maturity models should be created in an iterative process and carried out as a team work. For this reason, some colleagues from the Institute of Production Engineering at Graz University of Technology and external partners are involved.

As already mentioned, the respective components of the process chain and the sequence of implementation depend on the area of application of the company. Nevertheless, in the course of implementing the described process chain, some advantageous and also disadvantageous conditions have arisen. In addition to these conditions, particular attention has been paid to choosing elements first that have a very high positive effect on machine tool down times and the job preparation and are the least time-consuming to be implemented. Financial aspects have not been taken into account. For reasons of clarity, the selected maturity model, as shown in Figure 32, is divided into eight maturity levels, which are described within the following paragraphs.

---

[1] cf. Becker et al., (2009).

Maturity Level 0 - Initial State

The fictitious case of an SME which works as a contract manufacturer (small lot sizes up to lot size 1) has been chosen as the starting point. There are three lathe and three milling machine tools available, which are operated by three machine tool operators. The associated controls of the machine tools are from different manufacturers. The machine tools are programmed manually with 2D drawings serving as the main source of information. In addition, CAD software is used, which corresponds to the type of coupled systems and therefore does not offer any integrable CAM software, which is mainly used to support the machine tool operators with improved 2D drawings.

Maturity Level 1

The use of a CAM software can have the most positive effect on machine tool down times, as explained in Section 2.2. For this reason, a CAM software is introduced, which theoretically has an integrable CAD software. In this maturity level, CAD and CAM software are operated in coupled mode. In order to use CAM software, digital tools are required in addition to the DM of the machine tool. Although every CAM software has an internal tool management module, it is advisable to introduce a TMS which is independent from the CAM software. Basically, there is a significant difference between turning and milling in terms of the effort involved in creating the digital tools. Turning tools are much more complex and therefore more time-consuming than milling tools. Due to the fact that the manual programming of lathe machine tools is much easier than that of milling machine tools, within this maturity level only the milling is done with the CAM software. In lot size 1 production, a CAM simulation with simulated control is recommended, but a distinction must be made depending on the respective kinematics of the machine tool. For milling machine tools that only have 3 axes, a CAM simulation without consideration of the control is sufficient. For complex 5-axis machining, however, a CAM simulation with simulated control is recommended. Within the process chain presented above the production data (NC Code and associated documentation) are transferred from the PLM software to the machine tools. As explained in maturity level 7, the introduction of a PLM software only makes sense if the respective company has a certain size. In addition to storing the production data in a PLM software, there is also the possibility of storing them in a TMS and transferring them from the TMS to the machine tools by a method similar to SFC. If, as in this fictitious case, a PLM software does not make sense, this variant is to be preferred within this maturity level.

Maturity Level 2

In order to further reduce the machine tool down times, the measuring process of the tools must be shifted to a presetting and measuring machine. To enable the fastest possible measuring process, a presetting and measuring machine with CNC-operated axes is recommended. The most important point after the general implementation is the connection of the presetting and measuring machine to all machine tools that allow external measurement. The QR-code is selected as the data transfer method, which is printed on self-adhesive labels.

The next step is connecting the TMS to the presetting and measuring machine. Any measurement modes must be added to the previously created digitally complete tools in order to enable an automatic measurement process of the tools.

Maturity Level 3

The next step is to improve the set-up processes of the physically complete tools. To achieve this, a TDS is being implemented. In order to enable perfect synergies, the TMS and TDS should be bought from the same manufacturer. Due to this fact the digital components, created within maturity level 1, can be mirrored to the software of the TDS without changes.

The next step is registering the turning tools for the TDS. It is recommended that the tools are generated in the TMS without geometry and then mirrored back to the software of the TDS. The advantage of doing so is that the geometry can be added in a later step, but then the entries in the TDS do not have to be changed.

Maturity Level 4

Within this maturity level, CAM and TMS are introduced for lathe machine tools, in order to reduce machine tool down times. The previously created data-sets in the TMS for turning tools can be complemented with CAD data for the CAM application. For simple 2-axis turning operations, a CAM simulation without consideration of the control is sufficient. A CAM simulation with simulated control is recommended for complicated mill-turn machining.

Maturity Level 5

The next step is the introduction of a software for storing machining data, such as an MDL, to support the CAM programming. Functions from an MDL can also be taken over by the TMS, but for a certain number of different combinations of tools to machine tools, the management of the machining data in an MDL is advantageous.

Maturity Level 6

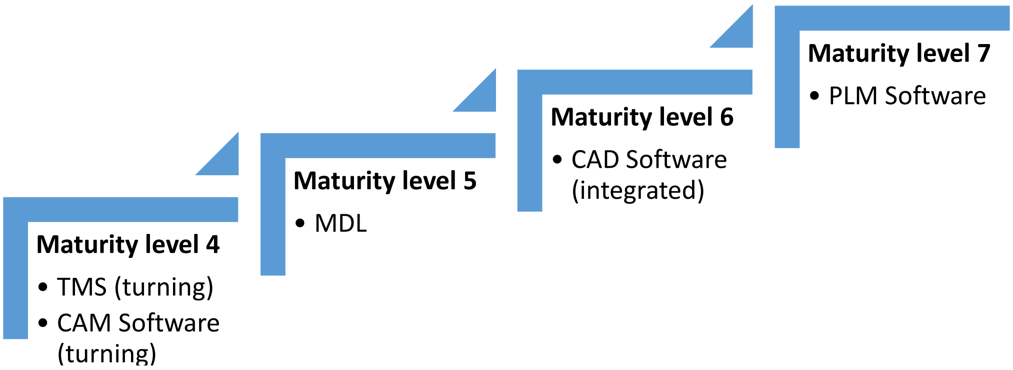
Within this maturity level the CAD software is changed to an integrated CAD software and therefore to an integrated CAD-CAM system. This procedure primarily supports CAM programming, as any adjustments to the CAD data can be made many times faster than with a coupled system.

Maturity Level 7

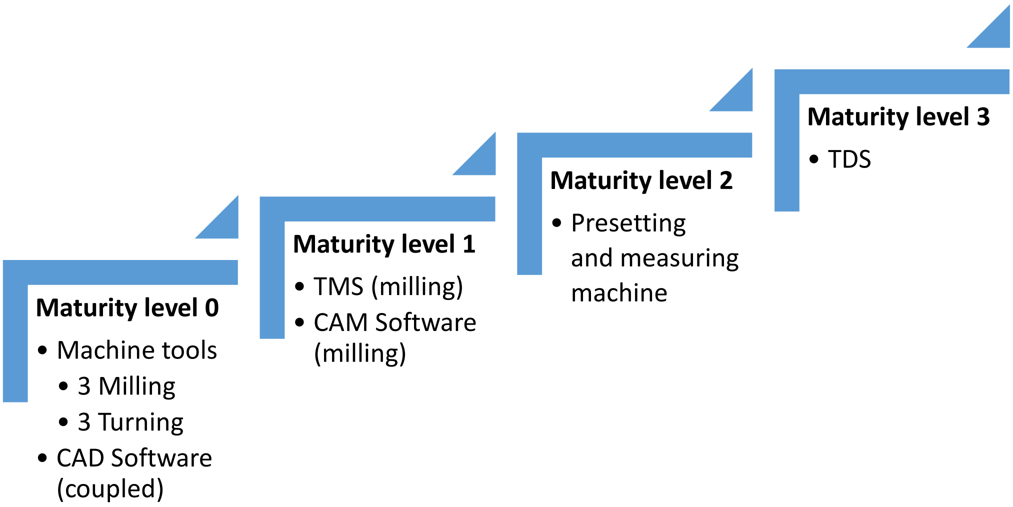
The last step to the chosen optimum is the introduction of a PLM software. This step makes sense only for companies with a certain size. Basically, a PLM system is preferable to a PDM system. Nevertheless, a PLM system would be introduced in this maturity level but only used as a PDM system. This has the advantage of professional data management, but the effort involved in introducing the system is limited. Furthermore, the PDM module can still be expanded to a complete PLM software in the future.

Suggested Maturity Level

Maturity level 7 is not suggested as an actual target for this fictional company. For this specific case, reaching maturity level 3 would be absolutely sufficient. The main reason for this is that the introduction of new systems is always associated with maintenance effort. The components up to maturity level 3 have a manageable implementation effort and a very good overall functionality.



(a) Maturity level 4 - 7



(b) Maturity level 0 - 3

Figure 32.: CAD-CAM-CNC Implementation Maturity Model
Source: Own illustration.

4. Evaluation of the Selected Process Chain

Within this chapter, the previously presented process chain is going to be evaluated. The PFMEA is used as a method for determining all relevant sources of error. In order to become aware of further problems, a quantitative survey has been carried out using a questionnaire. Discussions with experts from the industry serve as the basis for this survey. The aim of this chapter is to identify any development potential.

4.1. Process - Failure Mode and Effects Analysis

According to the standard (OENORM EN 60812), there are various procedures for carrying out a PFMEA. In the context of this work, the following standardized procedure is used. [1,2,3,4,5,6,7]

- Planning & Preparation
- Structure Analysis
- Function Analysis and Failure Analysis
- Risk Analysis
- Optimization
- Results Documentation

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[1] cf. Werdich, (2012), pp.21-95.
[2] cf. Hering / Schloske, (2019), pp.39-53.
[3] cf. Milekovic, (2017), Online-source [19.05.2020].
[4] cf. Knorr, (2017), Online-source [19.05.2020].
[5] cf. Systema Engineering, (2020), Online-source [19.05.2020].
[6] cf. Minautics, (2019), Online-source [19.05.2020].
[7] cf. OEVE OENORM EN 60812, (2006).

4.1.1. Planning & Preparation

The sections of the process chain shown in Figure 33 have been selected as the scope of the PFMEA. For this consideration it is assumed that the components to be manufactured have been correctly created via CAD. For this reason, the CAD section is completely excluded from the PFMEA assessment. According to the standard, a PFMEA should be done as a teamwork. For this reason, some colleagues from the Institute of Production Engineering at Graz University of Technology and external partners were integrated.

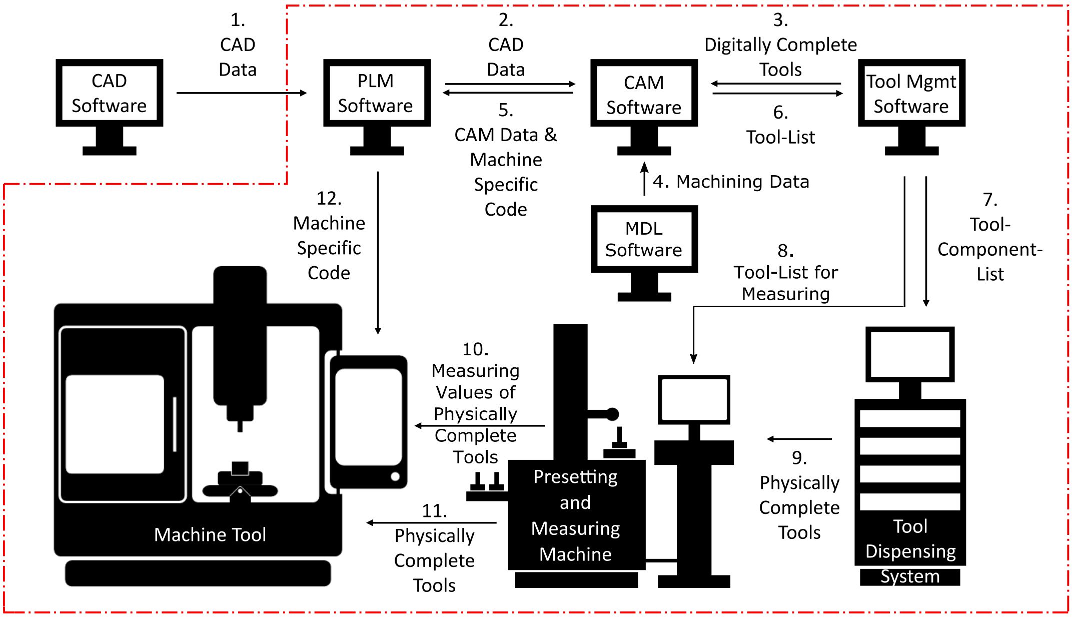

Figure 33.: Scope of the PFMEA
Source: Schmid / Pichler (2020).

4.1.2. Structure Analysis

In order to facilitate the process steps, a structure analysis has been carried out, following the elements of the process chain, as shown in Figure 34. In addition to the consideration in Figure 33, the step "Set-up area" has been added, since the assembly of a complete tool is suspected to be critical.

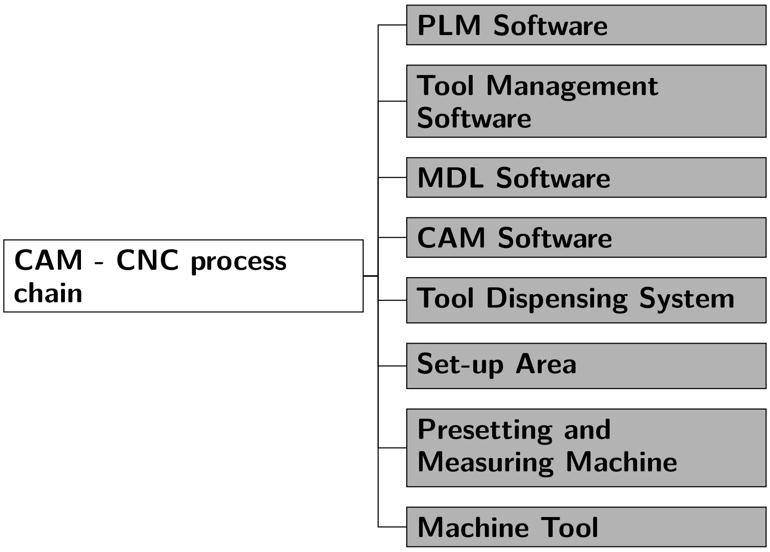

Figure 34.: Structure Analysis of the CAM - CNC process chain
Source: Own illustration.

4.1.3. Function and Failure Analysis

After the structure analysis, the functions to be considered (shown in green) are assigned to the individual elements (shown in grey) within the team. Since elements such as the "PLM Software" have a very wide range of functions, only those functions that were used in the CAM-CNC process chain are considered. After the Function Analysis, a Failure Analysis was carried out. Potential failure types (shown in red) were assigned to the individual functions. In the following Figures 35 to 42, Function Analysis and Failure Analysis are presented together for reasons of clarity. [8,9]

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[8] cf. Werdich, (2012), pp.31-34.

[9] cf. Werdich, (2012), pp.38-47.

4.1.3.1. PLM Software

In the following, the considered functions of the PLM system are briefly described and any potential errors are pointed out. A summary of the functions and associated errors is shown in Figure 35.

Function 1: Providing CAM templates

As explained in Subsection 2.2.3.1, the CAM automation method "Templates" is considered in the context of this work. The arising problem is that the creation and use of a template is based on a manual work task. Despite work instructions, general errors, such as, typing errors, cannot be excluded, however, the severity and the probability of occurrence are classified as very low. If errors occurred, they could be easily recognized.

Function 2: Saving and linking of the data

If any data is stored in a PLM software, these must be classified and named. If an error occurs, despite the input mask, problems can arise if the data are searched again at a later point in time. To counteract this problem, an impact analysis can be carried out within the PLM software. Although this analysis is time-consuming, all networked data can be found again regardless of the name and classification. The general risk of the malfunction mentioned is classified as low.

Function 3: Release of the data

After completion of the planning process of the respective data, they must go through a manual release process, which can be designed as desired. In order to reduce the error rate to a minimum, a four-eyes release process (release by two people) has been chosen. If incomplete data is released, this can lead to a serious damage to the machine tool. Applying the four-eyes principle, errors can be classified as extremely unlikely.

Function 4: Transfer of manufacturing data

The transfer of data is controlled automatically. The only manual work task in preparation is the assignment of a transfer destination. Here, too, the four-eyes release process is used and reduces the general error rate to a minimum, because the transfer destination is determined within the PLM software and released afterwards.

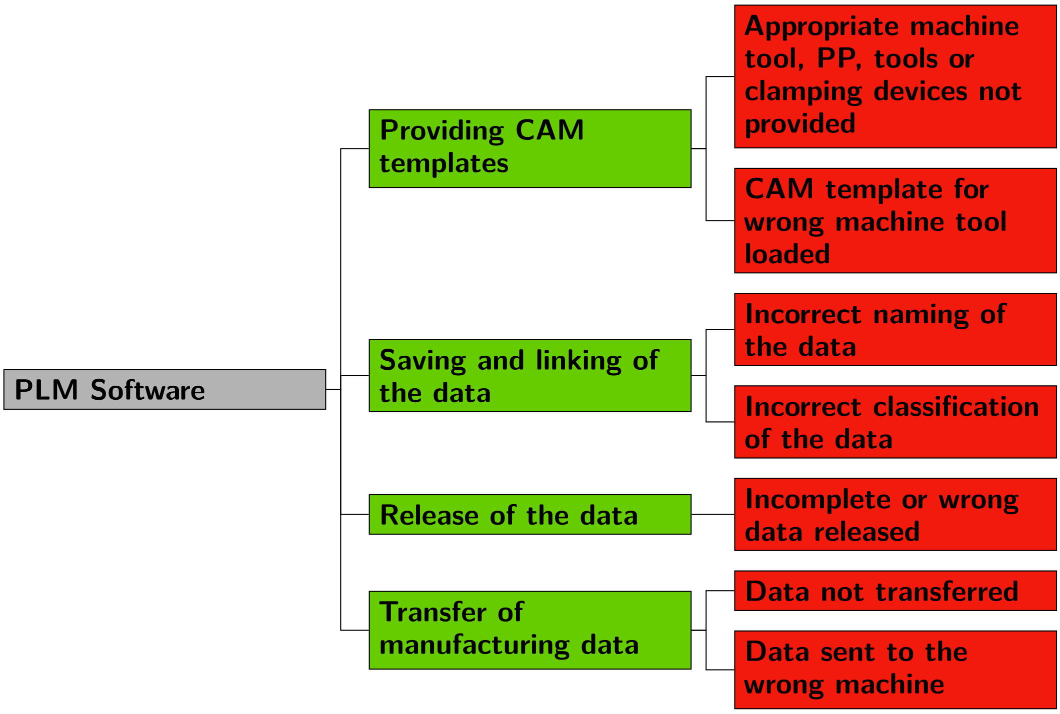

Figure 35.: Function and Failure Analysis of the PLM Software
Source: Own illustration.

4.1.3.2. Tool Management Software

Function 1: Generation of tool components

The components of digital tools can be created manually or downloaded from the websites of the tool manufacturers. Both methods are similar in terms of possible errors. When creating digital tool components, the software provides support at every point with an input mask and work instructions. The potential impact of an error of this type is classified as very high, due to a possible collision of the machine tool. If a mistake occurred, it would either be recognized during the assembly of the digital components into digitally complete tools or during the subsequent CAM simulation or on the presetting and measuring machine at the very latest. Despite these reasons, the general risk of malfunctions is classified as critical.

Function 2: Generation of complete tools

Similar to the generation of the tool components, manual tasks must be carried out when creating complete tools, which can lead to errors. The possible errors can be recognized during the CAM simulation or ultimately on the presetting and measuring machine and are therefore classified as moderate.

Function 3: Generation of tool component lists

The possible errors of this function indicate an incomplete generation of the digital components. As a result, components cannot be assigned and a set-up list cannot be created. These errors are not critical, as they can be recognized when the set-up list is created.

Function 4: Generation of tool set-up lists

If incorrect set-up information is generated, it can be recognized on the presetting and measuring machine during the measurement process. These errors are more severe than the ones mentioned above, but generally also classified as uncritical.

Function 5: Generation of measuring instructions

Basically, only few mistakes can be made within this process. The only notable mistake might be an incorrect measurement instruction. However, the probability that incorrect measuring values are generated due to incorrect measurement instructions is very low. The likely consequence of that error is that the measuring process cannot be carried out automatically.

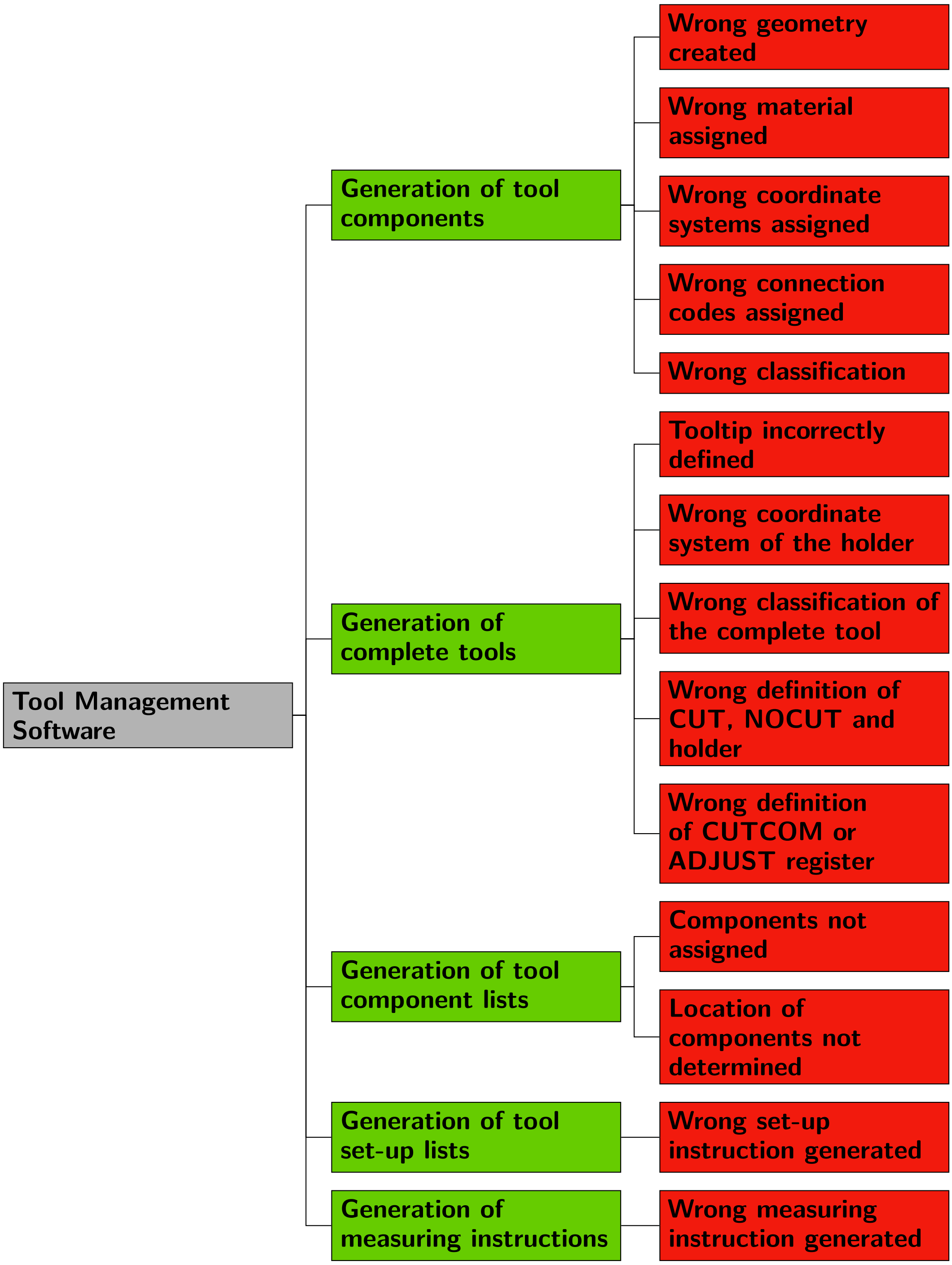

Figure 36.: Function and Failure Analysis of the Tool Management Software

Source: Own illustration.

4.1.3.3. MDL Software

Function 1: Saving of machining data

The MDL presented in this work requires data to be entered manually. If wrong data is entered, wrong data is sent to the CAM software and then the simulation is carried out with wrong machining data. The problem is that a CAM simulation in general is not designed to simulate machining data and this error would remain undetected. If the generated NC code is not checked before production, the wrong machining data can lead to tool damage or machine tool collisions. For this reason, this type of error is classified as very critical.

Function 2: Providing of machining data

If the MDL has not saved the required values, there is the possibility of an interpolation of the cutting speed and feed. All other associated parameters of the desired setting must be saved. Since the interpolation only works linearly between two neighboring values, an error can occur if the deviation is too high. This error cannot be detected by means of CAM simulation either and is therefore to be classified as very critical.

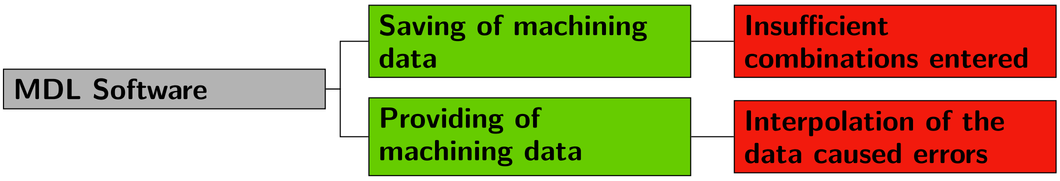

Figure 37.: Function and Failure Analysis of the MDL Software
Source: Own illustration.

4.1.3.4. CAM Software

Function 1: Import of the tool data

The import process of complete tools to the CAM software might not be possible. A TMS that has not been started or a network drive that is not connected can be listed as reasons. This error is classified as rather uncritical.

Function 2: Digital set-up process of the machine tool

If the digital set-up process of a machine tool is carried out insufficiently, this error might not be recognized during the CAM simulation. However, the use of templates reduces the likelihood of errors to a minimum.

Function 3: Planning of the manufacturing process

The planning of the manufacturing process using CAM software is not necessarily error-free. The severity of the potential errors is diverse. Due to the possibilities of work instructions, templates and analysis methods, the probability of incorrect planning is generally low. However, the selection of machining data despite the use of an MDL turns out to be a high potential for errors. Although there are ways to simulate this machining data, these methods are not as reliable as, for example, a collision analysis in a CAM simulation. To make matters worse, the error of an incorrectly defined machining data can only be discovered to a limited extent.

Function 4: Analysis of the manufacturing process

The analysis process of the CAM program is an essential part of the entire CAM programming. The possibility that an incorrect analysis method is chosen, despite the work instructions, is rather low. However, if the wrong method is used, a planning step can be overlooked and the workpiece might not be manufactured completely. Generally, this possible error is classified as uncritical.

Function 5: Generation of the NC code

Creating an NC code from a CAM program without simulation is not recommended, but it is technically possible. If an incorrect PP is selected, a collision on the real machine tool can occur. The use of templates and work instructions reduces the risk to a minimum.

Function 6: Generation of the Shop Documentation

The generation of a shop documentation is a manual task, in which a desired template must be selected manually. Due to work instructions, the possibility of an incorrect selection can be classified as very low. However, if an incorrect shop documentation is generated, the severity can be classified as high because of a possible collision of the machine tool.

Function 7: Export of the tool data

After the CAM planning has been completed, the tool management data must be exported manually. If this does not happen, a set-up list can not be generated. Again, the impact of this error can be classified as very low, since this error is immediately noticeable.

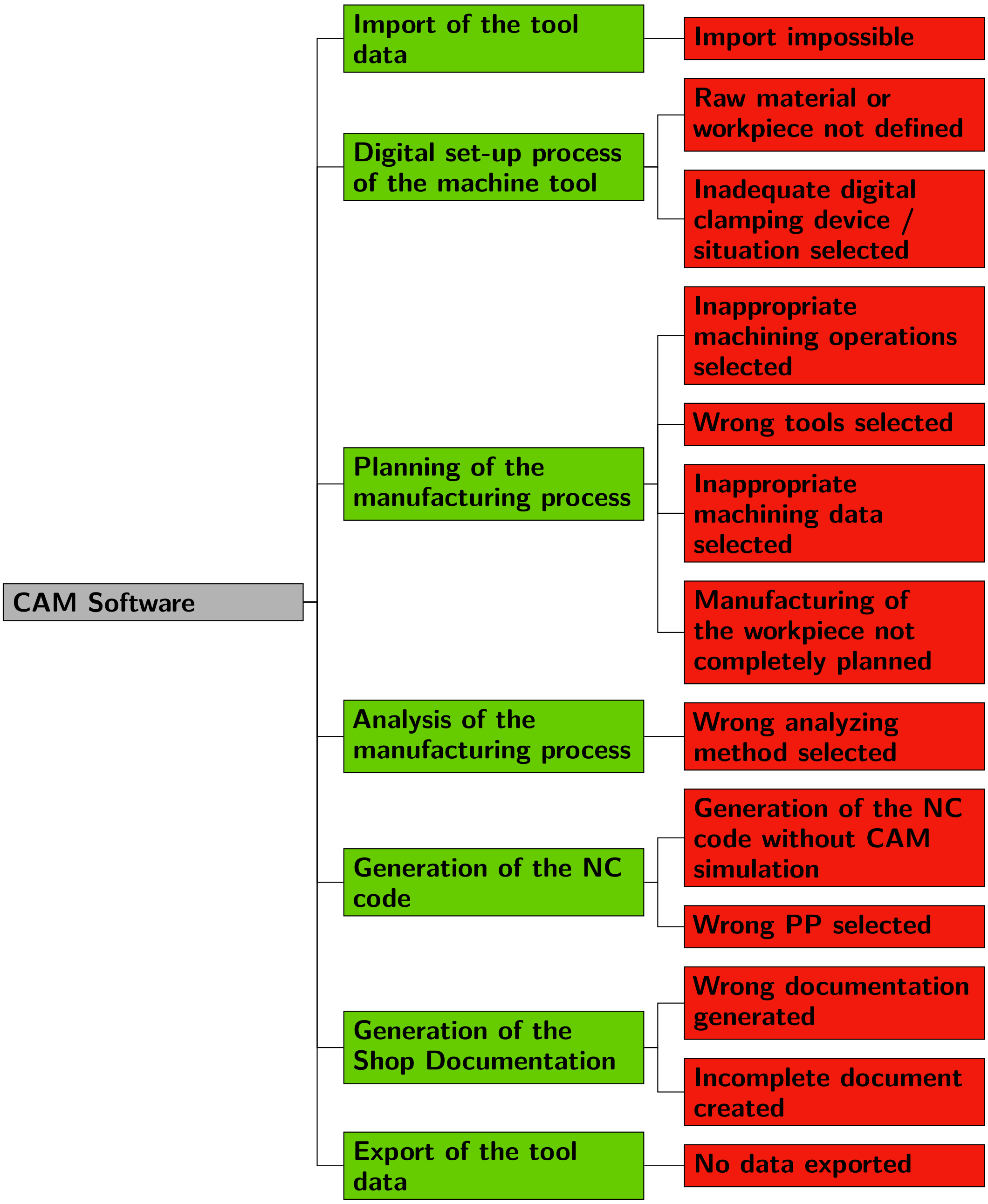

Figure 38.: Function and Failure Analysis of the CAM Software

Source: Own illustration.

4.1.3.5. Tool Dispensing System

Function 1: Storage of components and complete tools

The storage of components and complete tools is a manual work task that can not be checked automatically. If the components are incorrectly logged in, they can no longer be found by the system. If this is the case, the consequence is a manual search. This error is classified as very uncritical.

Function 2: Display of the storage locations

When a set-up list is printed on paper, the respective barcode might not be readable, because of a possible poor condition of the paper. If this is the case, the tool must be searched manually by typing in the name of it. The impact of this error is considered to be minor.

Function 3: Calculation of the stock of the tools

The correctness of the stock of the tools largely depends on the manual feeding and removal. The risk of an incorrect feeding or removal is limited due to the visual support of the TDS. If the stock is not displayed correctly, it can happen that a required tool is not available.

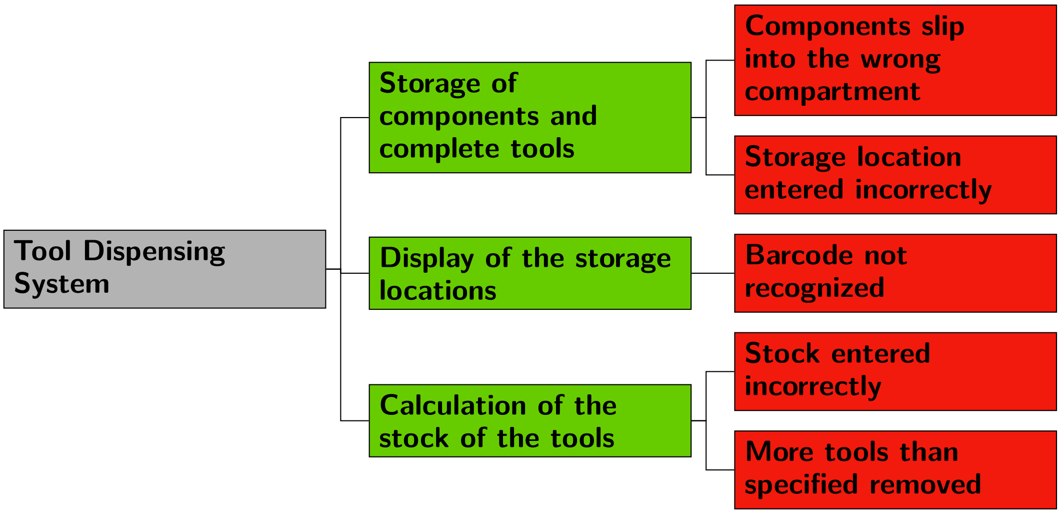

Figure 39.: Function and Failure Analysis of the tool dispensing system
Source: Own illustration.

4.1.3.6. Set-up Area

Function 1: Assembling of tool components into complete tools

When tool components are assembled into complete tools, these can generally be assembled with wrong components or with wrong clamping lengths. Both possibilities can be recognized by the presetting and measuring machine. For this reason, the general impact of these errors is classified as low.

Figure 40.: Function and Failure Analysis of the set-up area
Source: Own illustration.

4.1.3.7. Presetting and Measuring Machine

Function 1: Measuring of complete tools

Due to the method used that measurement settings are already defined within the digitally complete tool, an incorrect measurement method due to a wrong selected process can be classified as very low. It should be emphasized, however, that the tools must be dusted off before each measurement process. If this has not been done, the measurement results will be falsified. However, if incorrect measured values are generated, the severity of this error must be classified as high, because a collision can occur on the machine tool. Nevertheless, the error is recognizable and the probability of occurrence is low.

Function 2: Data transfer of the measured values

After the measuring process, the machine tool must be selected for which the QR-code with the measured values is to be created. This is a manual work task and is supported by work instructions. If a wrong machine tool is selected, an incorrect data set can be generated, which can lead to a collision. Due to the available work instructions, however, the probability of occurrence is very low. After the measurement process, the printed label must be attached correctly. Based on the work instructions, the general probability of an error is rated as low.

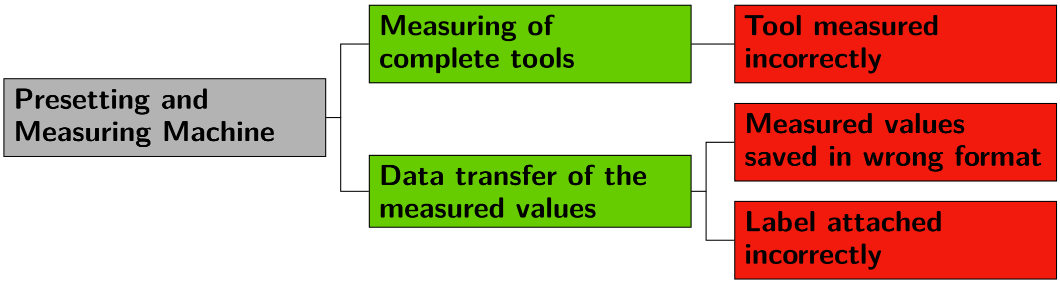

Figure 41.: Function and Failure Analysis of the presetting and measuring machine
Source: Own illustration.

4.1.3.8. Machine Tool

Function 1: Loading data by SFC

Basically, all those data which are loaded by SFC are released in the PLM software. Since the SFC is triggered by a manual entry, an error can occur in this case. The entry in SFC requires a combination of a part identification number and the desired machine tool. The probability that a positive search result will be returned despite an incorrect entry is very low. However, it should be mentioned that if an incorrect NC code was loaded, it could lead to a collision on the machine tool.

Function 2: Loading measured values of the tools

If an incorrect QR-code with measured values is generated, the code can also be loaded. If the control type of the machine tool is different, an error message is displayed. If the QR-code is not recognized, the values can be entered manually. If an error occurs within this function, the machine tool can be severely damaged. However, the probability of occurrence is rather low.

Function 3: Setting up complete tools

After an entry has been successfully created in the internal tool database of the machine tool using the QR-code, this entry must be loaded manually. The complete physical tool must then be set up manually. If the physical tool is set up when an incorrect entry is loaded, severe damage to the machine tool can occur. However, the probability of this error occurring is considered to be very low.

Function 4: Setting up clamping devices

The set-up process of the clamping devices is also a manual work task and a deviation of the real clamping devices from the digital ones in the CAM simulation is also critical. Due to automatically generated set-up lists with regard to clamping devices, the probability of occurrence is very low.

Function 5: Setting up raw materials

The set-up of the raw material is critical as well. However, due to the automatically generated work instructions using shop documentation, the probability of an error occurring is classified as low.

Function 6: Setting up zero points

Each NC code relates to defined zero points. These zero points must be entered in the machine tool. If the entered zero point on the machine tool deviates too much from the one in the CAM program, the machine tool can be severely damaged. Because of the automatically generated shop documentation, the probability of an error occurring can be classified as low.

Function 7: Loading the NC code

When an NC code is loaded using SFC, it is transferred to a network drive, which is integrated in the machine tool. Starting from this network drive, the NC code must be selected manually. If this is not done, the previously executed NC code is executed again and damage can be the result. The probability that such an error occurs is classified as very low.

Function 8: Execution of the manufacturing process

The processing of the NC code can be influenced by the positions of the potentiometers of speed and feed. Depending on the manufacturer of the machine tool, the values can be manipulated from 0% to 200%. The problem here is that the NC code is designed for 100%. If there are large deviations, damage to the tools might occur.

Figure 42.: Function and Failure Analysis of the machine tool

Source: Own illustration.

4.1.4. Risk Analysis

Within the Risk Analysis, specific root causes and effects are assigned to the error types. These are then evaluated (1-10) for probability of Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) is then calculated by multiplying S, O and D. According to the standard, the sole use of the RPN is not reliable, because a very high S and low O and D can be assessed with a comparatively low RPN. Failures with medium values at S, O and D, on the other hand, are rated more critically. For this reason, the multiplied values of S and O are considered in addition to the RPN. [10,11]

Within the following subsections the most critical values of the Risk Analysis, which are summarized in Table 18, are discussed in more detail. The entire Risk Analysis is attached in the appendix of this thesis (Section A.2).

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[10] cf. Werdich, (2012), pp.50-56.

[11] cf. OEVE OENORM EN 60812, (2006).

4.1.4.1. Tool Management Software

If digital tools are created that do not correspond to the real geometry, a collision can occur on the real machine tool. The probability of such a deviation due to several security mechanisms is lower than other potential errors mentioned here, but not negligible. (RPN=60)

4.1.4.2. MDL Software

The most striking potential error according to the Risk Analysis is the use of incorrect machining data.

The main reason is error nr. 22, which stands for the entry of insufficient combinations in the MDL. A CAM operator is not obliged to use these values, but a recommendation by the MDL with incorrect values can influence the operator. (RPN=120)
Error nr. 23 is responsible for the wrong interpolation of the suggested machining data of the MDL. If two correct values for the interpolation differ greatly, this can result in an inadequate value with regard to machining data. This potential error is viewed critically, above all because a CAM operator does not receive a message that an interpolation by the MDL has been carried out. (RPN=210)

4.1.4.3. CAM Software

The striking errors that can be assigned to this structure element basically result from the two errors previously mentioned. A CAM operator must select suitable machining data, which can be suggested, for example, by an MDL. If trust is placed in incorrectly suggested values, a collision of the machine tool is possible in worst case. (RPN=180)

4.1.4.4. Machine Tool

An incorrectly assigned measured value for an incorrect physically complete tool is the most striking error within this structure element. Despite the very low probability of occurrence, this error should not be underestimated due to the high severity of the possible error and low detection probability. (RPN=60)

Table 18.: PFMEA - summary of the Risk Analysis
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Structure: Tool Management Software			**Function: Generation of tool components**							
8	Wrong geometry created	Possible collision on the real machine tool	10	Data mixed up	Input mask with instructions	3	CAM simulation or presetting machine	2	30	60
Structure: MDL Software			**Function: Saving of machining data**							
22	Insufficient combinations entered	CAM operator influenced by wrong values	5	Typing error	Work instruction	4	Visual inspection	6	20	120
23	Interpolation of the data caused errors	CAM operator influenced by wrong values	5	Too few values in the database	Work instruction	7	Visual inspection	6	35	210
Structure: CAM Software			**Function: Planning of the manufacturing process**							
29	Inappropriate machining data selected	Quality of the real workpiece is insufficient	7	Human error	MDL	3	Visual inspection	6	21	126
		Possible collision on the real machine tool	10	Human error	MDL	3	Visual inspection	6	30	180
Structure: Machine Tool			**Function: Setting up complete tools**							
50	Measured values assigned to wrong tools	Possible collision on the real machine tool	10	Typing error	QR-code scan	1	Visual inspection	6	10	60

4.2. Survey Among Experts from Industry

In the course of the work on this thesis, many conversations (~ 30) have been held with experts from the industry. After these discussions, a questionnaire was designed to collect more information on problems with regard to the CAD-CAM-CNC process chain. The aim of this survey is primarily to identify general, relevant challenges in the field of digitalization of machine tools and tool management. These general challenges should be considered in addition to the problem areas previously identified using PFMEA.

The survey has been carried out using Google Forms and relevant specialist forums on the Internet served as the platform for the survey. Figures 43 to 47 show the results of the survey (33 participants; estimated response rate of 3.7%) which are divided into results from participants from SMEs and LEs.

An even number of answers has been chosen, ranging from "Strongly disagree" to "Strongly agree". The respective numerical values have been rounded for reasons of clarity. [12] The results were evaluated by summarizing the categories "Strongly disagree", "Disagree" and "Agree", "Strongly Agree". These categories were then checked for significant differences.

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[12] cf. Porst, (2014), pp.71-98.

Are the CAD-CAM-CNC products available on the market too complicated or complex?

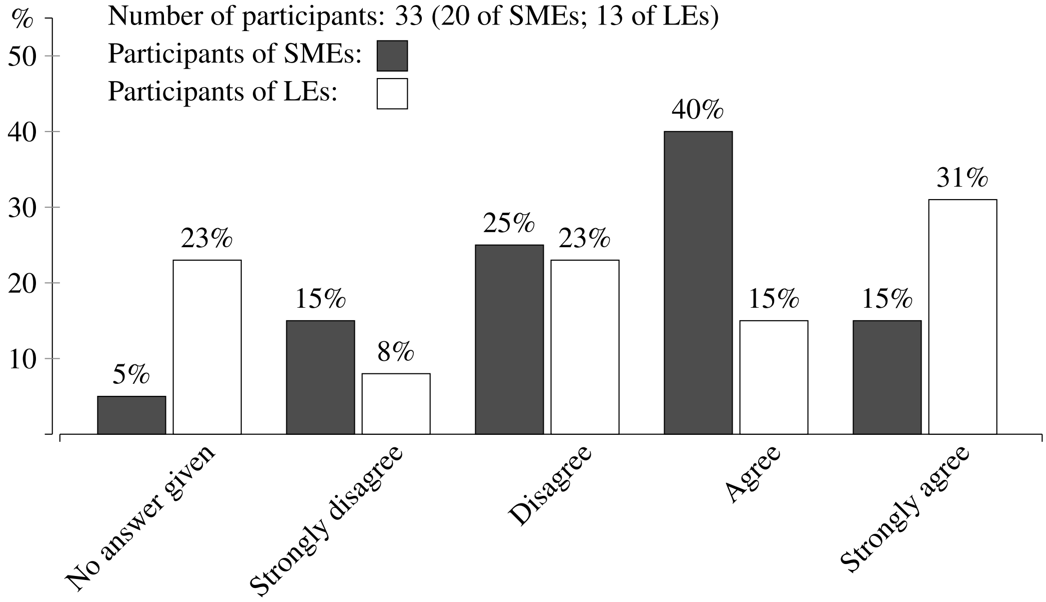

Figure 43.: Survey results divided into participants from Small and Medium sized Enterprises and Large Enterprises

Are the CAD-CAM-CNC products too diverse to choose an optimal implementation strategy?

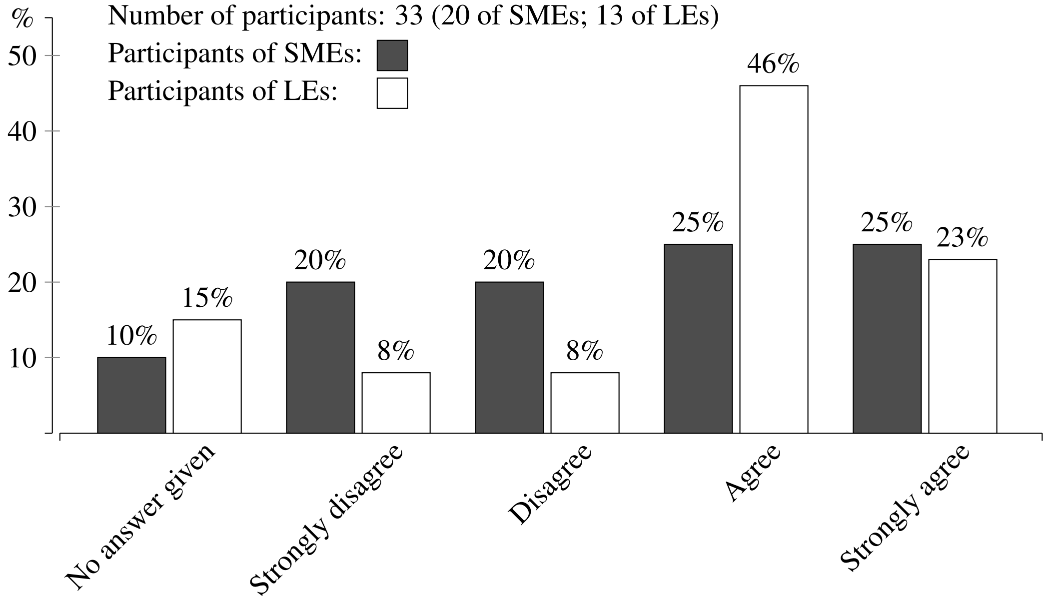

Figure 44.: Survey results divided into participants from Small and Medium sized Enterprises and Large Enterprises

Is the effort of creating a tool management database for the CAM planning too high?

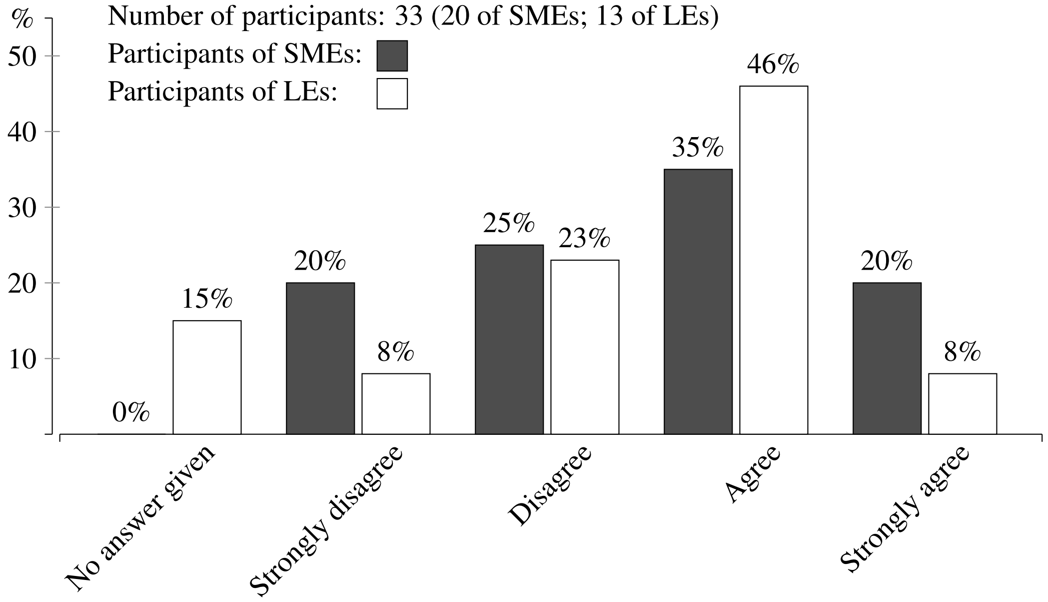

Figure 45.: Survey results divided into participants from Small and Medium sized Enterprises and Large Enterprises

Can CAD data of tool components if downloaded from the Internet be used, concerning the correctness of the data without reworking for CAM systems?

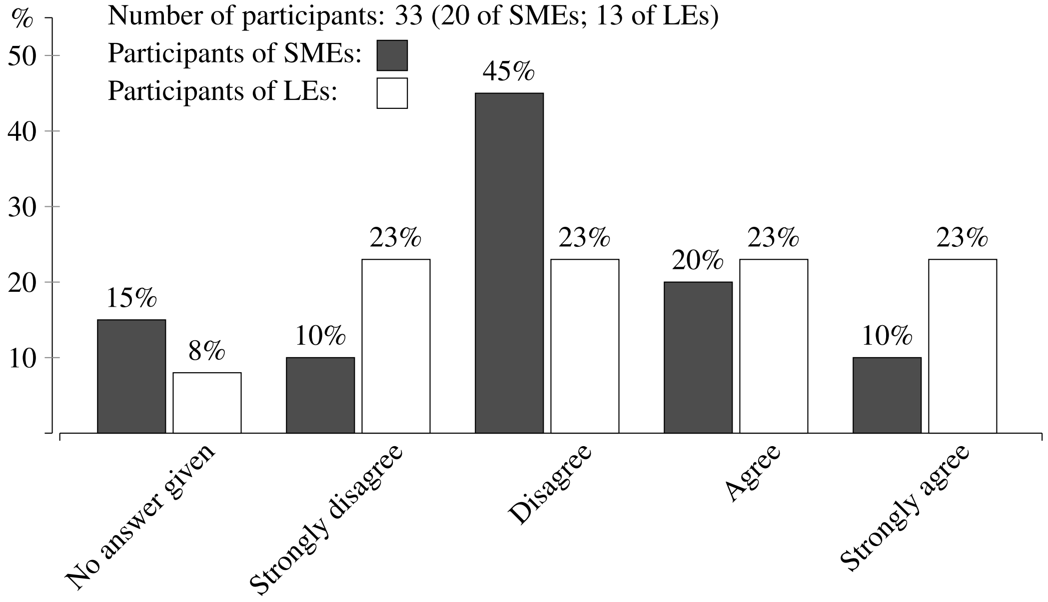

Figure 46.: Survey results divided into participants from Small and Medium sized Enterprises and Large Enterprises

Is the manufacturer information on machining data reliable?

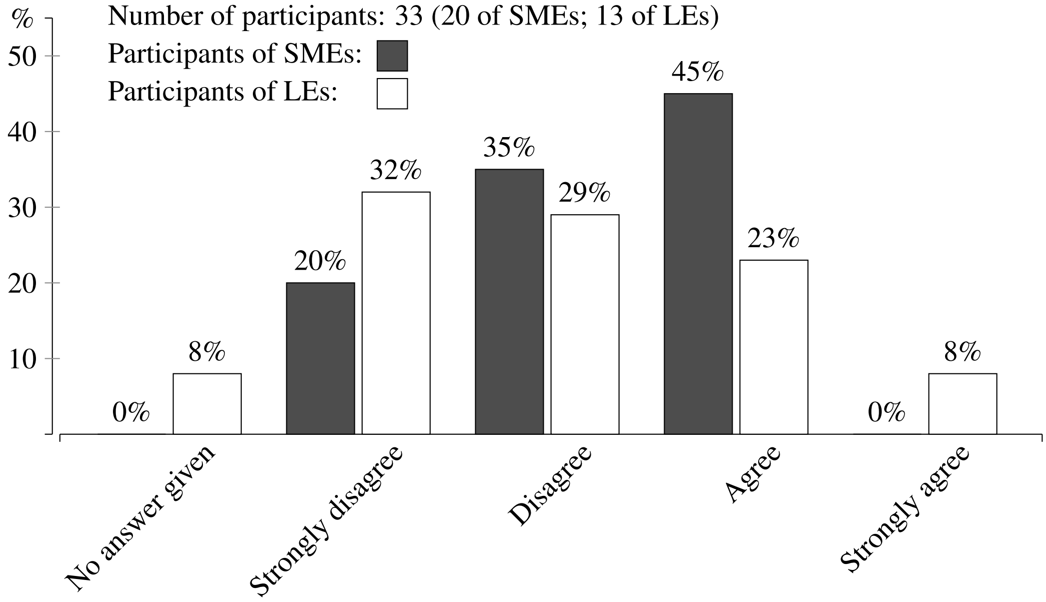

Figure 47.: Survey results divided into participants from Small and Medium sized Enterprises and Large Enterprises

Are the CAD-CAM-CNC products available on the market too complicated or complex?

Yes, based on the survey results, these are too complicated or complex.

Are the CAD-CAM-CNC products too diverse to choose an optimal implementation strategy?

Yes, based on the survey results, these are too diverse.

Is the effort of creating a tool management database for the CAM planning too high?

Yes, based on the survey results, the effort is too high.

Can CAD data of tool components if downloaded from the Internet be used, concerning the correctness of the data without reworking for CAM systems?

No, based on the survey results, the data cannot be used without reworking.

Is the manufacturer information on machining data reliable?

No, based on the survey results, the manufacturer information is not reliable.

5. Optimization of the Process Chain

This chapter describes the experimental implementation of the solution approaches that are used to solve the following selected challenges.

A major problem within the CAD-CAM-CNC process chain is the high effort that has to be put in to filling the databases with suitable data. Reasons for this problem are the creation of geometry data for the tools for CAM planning and the associated machining data. In addition to the high effort, both types of these data can be classified as very critical. If these data are entered incorrectly, it can cause severe damage to a machine tool. Furthermore, by rounding the values of the machining data based on the MDL, a completely wrong value can be passed on. For this reason, this problem must also be classified as critical.

5.1. Solution Approaches

An important delimitation of the following approaches are the terms verification and validation, which are defined as follows by using the standard (DIN EN ISO 9000):

Verification: *"Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. The objective evidence needed for a verification can be the result of an inspection or of other forms of determination such as performing alternative calculations or reviewing documents. The activities carried out for verification are sometimes called a qualification process."* [1]
Validation: *"Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled. The objective evidence needed for a validation is the result of a test or other form of determination such as performing alternative calculations or reviewing documents."* [1]

---

[1] DIN EN ISO 9000, (2015).

5.1.1. Closed-Loop Manufacturing for Validated Machining Data

In order to eliminate the problem of the high effort of filling an MDL with correct values, the process chain previously described is expanded by path 13, as shown in Figure 48. The basic idea is the import of validated machining data into an MDL to make them available again for future CAM planning. The aim of this approach is a CLM-based loop for validated machining data, which compares programmed TARGET machining data with ACTUAL machining data and saves the ACTUAL data after an evaluation into the MDL. This process runs in the background (semi -) automatically. Stored data records are not considered as frozen and can be adjusted by the process itself by going through the loop several times. The transfer of the required data from the CAM software to the machine tool is made possible by a DM, which has been developed within this thesis and is described in more detail in Section 5.2. The validated machining data is transferred via Open Platform Communications Unified Architecture (OPC UA), as explained in more detail in Subsection 5.4.1. The evaluation and the import of the selected data into the MDL are explained in Subsection 5.4.2 and 5.4.3. [2,3]

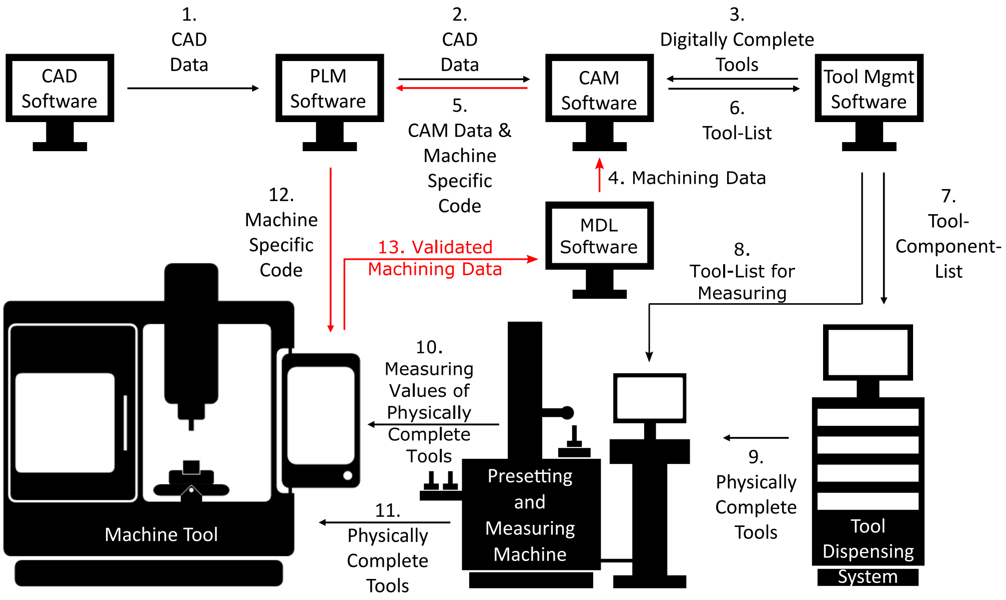

Figure 48.: Closed-Loop Manufacturing for validated machining data
Source: Schmid et al. (2021).

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[2] cf. Schmid et al., (2020b).
[3] cf. Schmid et al., (2021).

5.1.2. Verification Mechanism of Machining Data of New NC Codes

As already mentioned, an MDL interpolates the required values. This process works very well if there are enough values in the database. If there are too few values in the database, an incorrect output may result. A general number for sufficient or insufficient values in an MDL cannot be given, since suitable values must be available for every interpolation. An interpolation error can only be ruled out by manually checking the output data, which would result in a rather high effort. To reduce this effort to a minimum, an application was programmed which enables a check and thus verification of future generated NC codes with regard to the use of machining data from the MDL. The developed tool is described in detail in Section 5.5. [4]

5.1.3. Automatic Preparation of Scanned Tools for CAM Application

Based on the responses of the survey related to the high effort of creating a tool management database for CAM planning, an alternative approach has been developed. Starting from the state of the art, a complete tool can be 3D-scanned by a presetting and measuring machine. After manual preparation, the scanned tool can be used in the CAM software. This preparation is roughly as time-consuming as if the tool had to be modeled from scratch. To optimize this process, the idea has been developed to automate this preparation process. The basic idea is that the processes for preparing a scanned tool are always similar and the rotationally symmetrical geometry of a milling tool is also similar. This similarity is used to automate this process, which is explained in more detail in Section 5.6 and shown qualitatively in Figure 49. This process has been given the number 0 because it has to be understood as the basis for the entire process chain and should therefore be carried out first.

---

[4] cf. Schmid et al., (2020a).

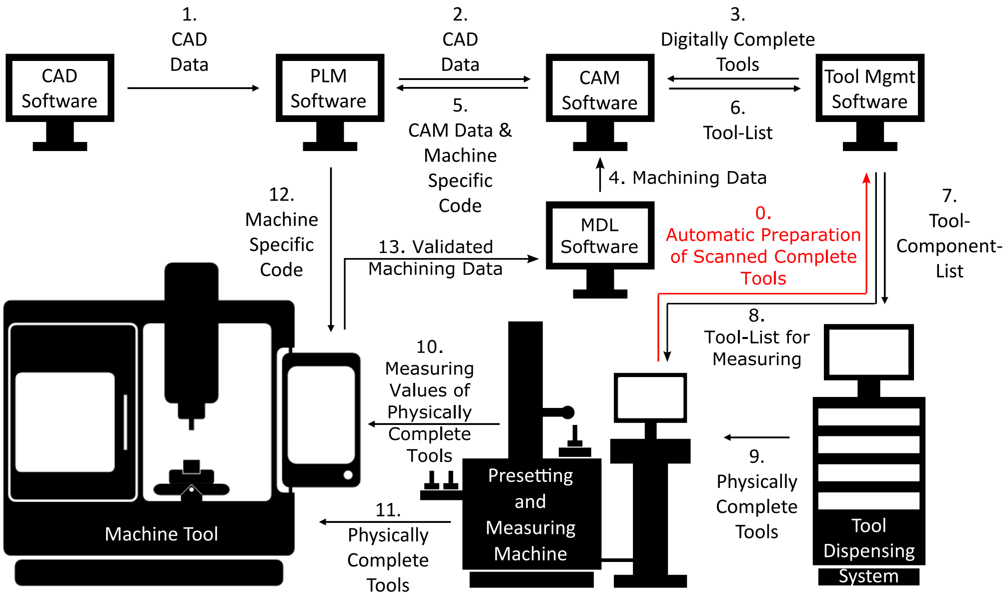


Figure 49.: Automatic preparation of scanned complete tools for CAM application
Source: Schmid / Pichler (2020).

5.2. Development of the Research Digital Model

This section describes the development of the DM that is used to enable the CLM approach, as described in Subsection 5.1.1. The most important and innovative part for the necessary data transfer is a specially developed PP which is described in Subsection 5.2.4.

The regarded machine tool is a 5-axis simultaneous milling machine tool by the brand SPINNER U5-630 with a Sinumerik 840D sl control system. The associated kinematics are shown in Figure 54b. Since a DM with emulated control and a DM with simulated control are used in different planning stages of the CAM application, the generation of both variants is necessary and is described in the following subsections. At the beginning of the implementation of a DM, a data extraction of the respective machine tool must be done and the CAD data must be adapted, which is described in each of the cases below.

5.2.1. Reading out Specific Machine Data Using a Commissioning Archive

With Sinumerik controls there is the possibility of a data extraction using a so-called commissioning archive. The content of such an archive is very rich, as shown in Table 19. The information from the NC data, as listed in the first row, is mainly required to create a DM of a machine tool. These archives are structured in tabular form and the entries are marked with five-digit key numbers, also called machine data numbers. Table 20 shows an extract from a sample archive. [5]

Table 19.: Complete content of a commissioning archive
Source: Siemens AG (2018a), pp.319-323.

Components	**Data**
NC data	• Machine data • Setting data • Option data • Tool and magazine data • Global and local user data • Zero offsets • Compensation data • R parameters • Workpieces, global part programs and sub-programs • Standard and user cycles • Definitions and macros • Compile cycles
Programmable Logic Controller data	• Organization blocks • Function blocks • Functions • Data blocks • System function blocks • System functions • System data blocks
HMI data	• Alarm notifications • Workpiece templates • Software applications • Display configurations • Online help files • Version data • Reports • Program lists • Dictionaries • Data backups • Program on a local drive

---

[5] cf. SPINNER Werkzeugmaschinenfabrik GmbH, (2019).

Table 20.: Axis and drive data of the X-axis from an extracted commissioning archive
Source: Schmid et al. (2020a).

Description	**Machine data number**	**Value**	**Unit**
Machine axis name	10000	X1	-
Logical axis	10002	AX1	-
Rotary axis	30300	0	-
Modulo conversion for rotary axis	30310	0	-
Axis number	35000	0	-
Velocity	32000	48000	mm \ min
Acceleration	32300	2.5	m \ s ^{2}
Jerk limit	32431	20	-
Jump ability	32310	1.2	-
KV Factor	32200	2	
Axis limit min	36100	-364	mm
Axis limit max	36110	266	mm

5.2.2. Simplification and Adaptation of the CAD Data of the Machine Tool

In order to enable the creation of a DM of a machine tool, CAD data of the respective machine tool are required. To make the calculation for the CAM software as straightforward as possible, these CAD data must be as simple as possible. CAD data are usually made available in a very detailed way, which is a problem for a CAM simulation due to very high performance losses. Due to this fact, the CAD data had to be simplified in some places. In addition to simplifying the shape, the number of individual parts should also be reduced. The CAD data of the machine tool presented in this work have been reduced from more than 1000 to 8 individual parts, as shown in Figure 50. Furthermore, the zero point and the axis alignment of the CAD data must match the zero point and the alignment of the axes of the real machine tool. It is particularly essential that each individual part of the assembly is placed on the zero point and not aligned with each other. Otherwise, the movements would cause conflicts during the simulation.

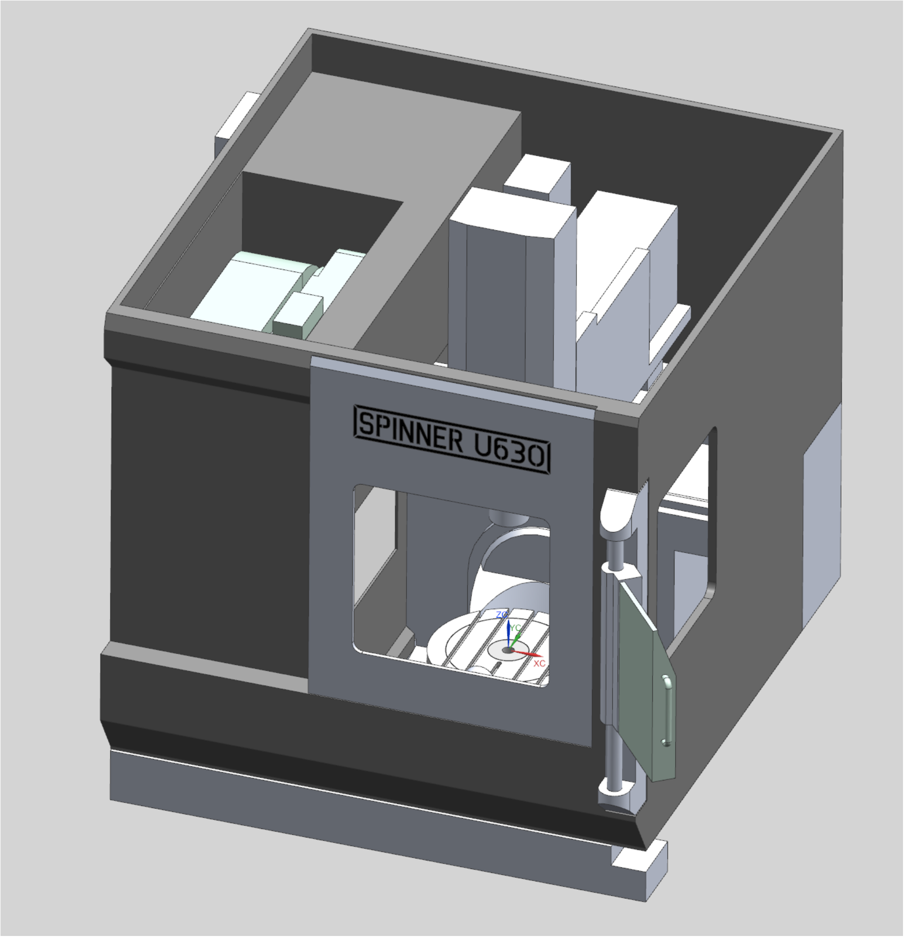


Figure 50.: Simplified CAD data of the SPINNER U5-630 machine tool
Source: Own illustration.

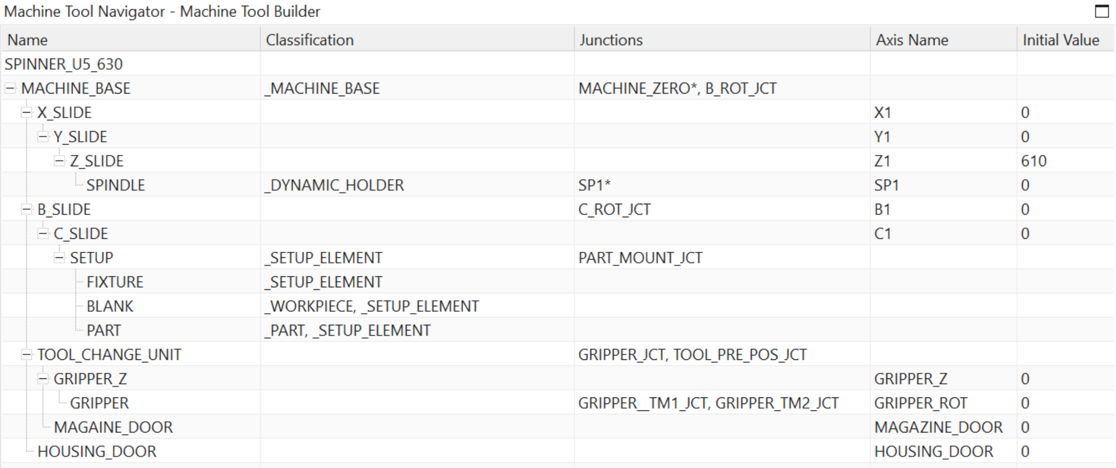
5.2.3. Kinematic Model of the Machine Tool

This subsection explains how a kinematic model is generated by using the "Machine Tool Builder" (MTB) application from Siemens NX. Within that application the previously simplified assembly of the machine tool is loaded into a new assembly, which is then loaded to the manufacturing environment in Siemens NX. [6]

---

[6] cf. IIM TU Darmstadt, (2015k), Online-source [10.04.2020].

To create a kinematic model of a machine tool, the associated structure must be created with the desired components. This structure has to be understood as some additional individual part that has to be added to the CAD data using the MTB. The hierarchical structure must be absolutely identical to the structure of the real machine tool and starts with the base component (MACHINE_BASE) at the top, as shown in Figure 51. The names of the individual components are not relevant, it is only important that the names of the respective axes (X1, Y1, Z1, SP1, B1 and C1) match with the internal name of the real machine tool. [7,8,9,10] Another issue is the definition of the whole clamping set-up of the machine tool, which was named SETUP in this structure. The clamping device (FIXTURE), the raw material (BLANK) and the actual workpiece (PART) are examined separately. With the SETUP element, it is necessary to insert a connection that lies on the work surface and is called PART_MOUNT_JCT. The orientation of this connection determines the position of the workpiece. [11,12] After the hierarchical structure has been set up, the individual components can be assigned to the different axes. In addition to the assignment, the components must also be classified. Table 21 provides an overview of the possible types of classification. After this has been done, the axes can be assigned with various attributes, as shown in Figure 52. For this step, the values must be taken from the associated commissioning archive. [13,14]



Machine Tool Navigator - Machine Tool Builder

Name	Classification	Junctions	Axis Name	Initial Value
SPINNER_U5_630				
MACHINE_BASE	_MACHINE_BASE	MACHINE_ZERO*, B_ROT_JCT		
X_SLIDE			X1	0
Y_SLIDE			Y1	0
Z_SLIDE			Z1	610
SPINDLE	_DYNAMIC_HOLDER	SP1*	SP1	0
B_SLIDE		C_ROT_JCT	B1	0
C_SLIDE			C1	0
SETUP	_SETUP_ELEMENT	PART_MOUNT_JCT		
FIXTURE	_SETUP_ELEMENT			
BLANK	_WORKPIECE, _SETUP_ELEMENT			
PART	_PART, _SETUP_ELEMENT			
TOOL_CHANGE_UNIT		GRIPPER_JCT, TOOL_PRE_POS_JCT		
GRIPPER_Z			GRIPPER_Z	0
GRIPPER		GRIPPER__TM1_JCT, GRIPPER_TM2_JCT	GRIPPER_ROT	0
MAGAINE_DOOR			MAGAZINE_DOOR	0
HOUSING_DOOR			HOUSING_DOOR	0

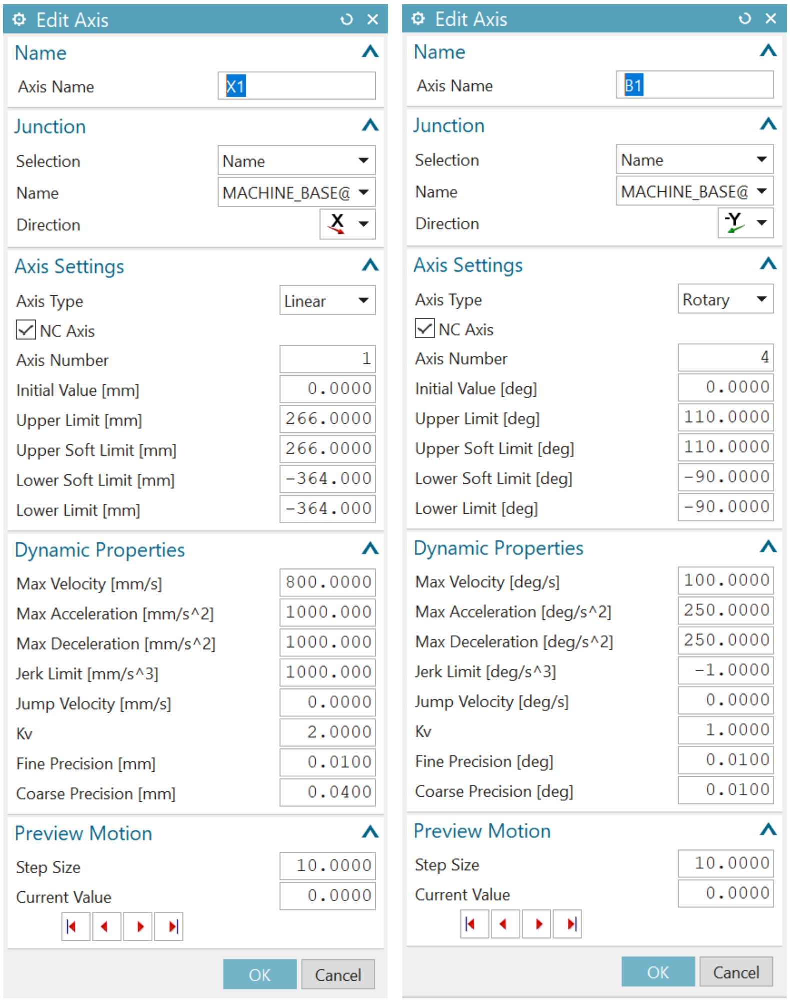
Figure 51.: Hierarchical structure of the kinematic model
Source: Own illustration.

---

[7] cf. IIM TU Darmstadt, (2015i), Online-source [10.04.2020].
[8] cf. IIM TU Darmstadt, (2015h), Online-source [10.04.2020].
[9] cf. Armendia et al., (2019), pp.42-44.
[10] cf. IIM TU Darmstadt, (2015o), Online-source [10.04.2020].
[11] cf. IIM TU Darmstadt, (2015n), Online-source [10.04.2020].
[12] cf. Siemens, (2018c), Online-source [07.02.2020].
[13] cf. IIM TU Darmstadt, (2015j), Online-source [10.04.2020].
[14] cf. Siemens, (2018e), Online-source [07.02.2020].

Table 21.: Important classification types
Source: IIM TU Darmstadt (2015j), Online-source [10.04.2020].

Class name	**Assignment of the component**
_DEVICE	Spindle
_DEVICE_HOLDER	Tool holder
_PART	Part component based on setup
_SETUP_ELEMENT	SETUP component, the workpiece is positioned here
_WORKPIECE	BLANK component based on setup



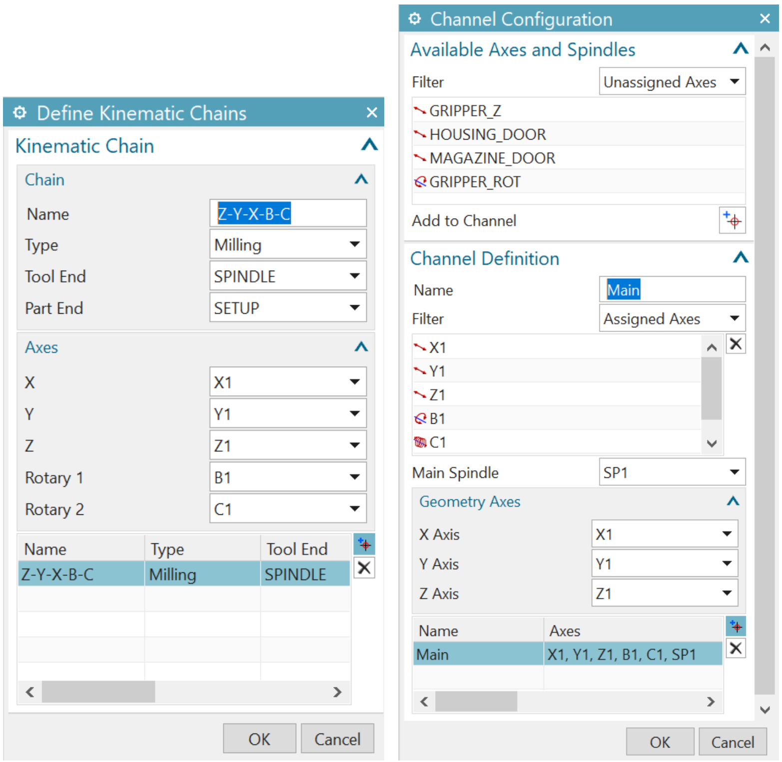
	X1	B1
Name		
Axis Name	X1	B1
Junction		
Selection	Name	Name
Name	MACHINE_BASE@	MACHINE_BASE@
Direction	X	Y
Axis Settings		
Axis Type	Linear	Rotary
☑ NC Axis		
Axis Number	1	4
Initial Value [mm] / [deg]	0.0000	0.0000
Upper Limit [mm] / [deg]	266.0000	110.0000
Upper Soft Limit [mm] / [deg]	266.0000	110.0000
Lower Soft Limit [mm] / [deg]	-364.000	-90.0000
Lower Limit [mm] / [deg]	-364.000	-90.0000
Dynamic Properties		
Max Velocity [mm/s] / [deg/s]	800.0000	100.0000
Max Acceleration [mm/s^2] / [deg/s^2]	1000.000	250.0000
Max Deceleration [mm/s^2] / [deg/s^2]	1000.000	250.0000
Jerk Limit [mm/s^3] / [deg/s^3]	1000.000	-1.0000
Jump Velocity [mm/s] / [deg/s]	0.0000	0.0000
Kv	2.0000	1.0000
Fine Precision [mm] / [deg]	0.0100	0.0100
Coarse Precision [mm] / [deg]	0.0400	0.0100
Preview Motion		
Step Size	10.0000	10.0000
Current Value	0.0000	0.0000

(a) X1 (b) B1

Figure 52.: MTB settings of different axes
Source: Own illustration.

The last steps in generating the kinematic model are the definitions of the kinematic chains and the channel configuration. Despite the hierarchical structure of the kinematic model, the kinematic chain must be defined explicitly, since the structure, which is responsible for the machining, must be emphasized. Figure 53a illustrates this as an example. If a machine tool has several kinematic chains available, then these must be defined several times. [15]

In addition to the kinematic chain, the channel must also be defined. Axes and spindles, which are referenced to a cutting edge, are assigned to a channel. Only these axes and spindles can be moved by using a program processed in a channel. This is particularly relevant for machine tools with multiple channels. The machine tool considered in this thesis only has one channel, but this one must also be defined. Axes that are not relevant in terms of machining must not be listed, as shown in Figure 53b. [16]



Name: Z-Y-X-B-C
Type: Milling
Tool End: SPINDLE
Part End: SETUP
X: X1
Y: Y1
Z: Z1
Rotary 1: B1
Rotary 2: C1

Name	Type	Tool End
Z-Y-X-B-C	Milling	SPINDLE

Filter: Unassigned Axes
GRIPPER_Z
HOUSING_DOOR
MAGAZINE_DOOR
GRIPPER_ROT
Add to Channel

Name: Main
Filter: Assigned Axes
X1
Y1
Z1
B1
C1
Main Spindle: SP1
X Axis: X1
Y Axis: Y1
Z Axis: Z1

Name	Axes
Main	X1, Y1, Z1, B1, C1, SP1

(a) Definition of the kinematic chain (b) Channel configuration

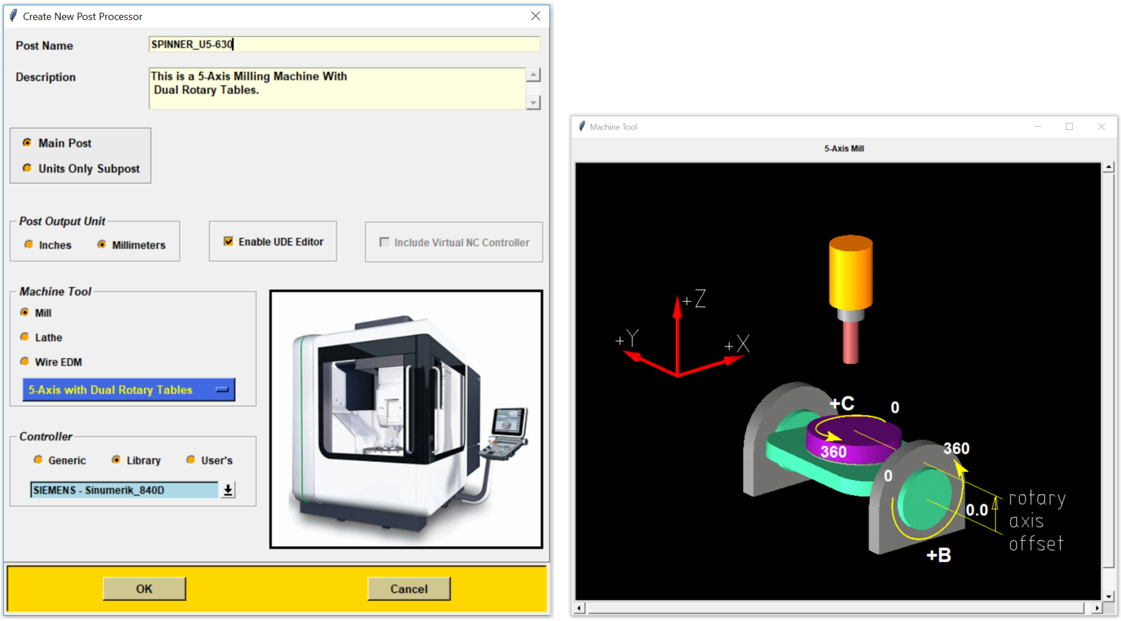
Figure 53.: Final MTB settings
Source: Own illustration.

---

[15] cf. Sanchez Gomez et al., (2016).
[16] cf. Siemens AG, (2017), p.400.

5.2.4. Post-processor

The software "Post Builder" is used to program the desired PP. At the beginning, basic settings like the units, kinematics and the control must be set, as shown in Figure 54. After this step a preliminary PP is created which must be adapted to the conditions of the real machine tool. For example, the axes must be limited like the real machine tool and each function and cycle, as illustrated in Figures 55 and 56, must be checked for correctness and adjusted manually if necessary. To archive this, the values of the commissioning archive must be transferred. [17,18,19,20,21,22]
The functionality of the CLM approach is put into practice by specific PP programming. The approaches mentioned above for verifying the machining data in new NC codes as well as reading out the data via OPC UA, are made possible in both cases via so-called custom-commands (CC). These CCs can be used to influence the output of a PP in many ways. Two of them are described in the following.


Create New Post Processor

Post Name: SPINNER_U5-630

Description: This is a 5-Axis Milling Machine With Dual Rotary Tables.

● Main Post
○ Units Only Subpost

Post Output Unit
○ Inches ● Millimeters

☑ Enable UDE Editor

☐ Include Virtual NC Controller

Machine Tool
● Mill
○ Lathe
○ Wire EDM
5-Axis with Dual Rotary Tables

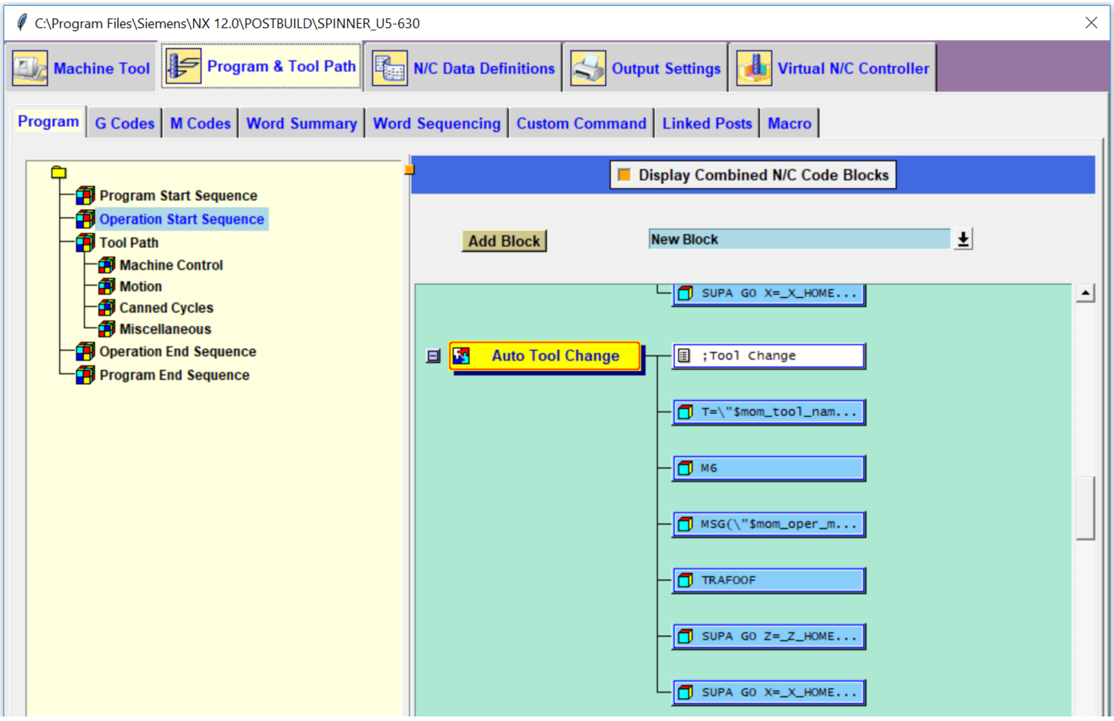
Controller
○ Generic ● Library ○ User's
SIEMENS - Sinumerik_840D

(a) Postbuilder home screen (b) Kinematics settings

Figure 54.: Creation of a post-processor using Post Builder
Source: Own illustration.

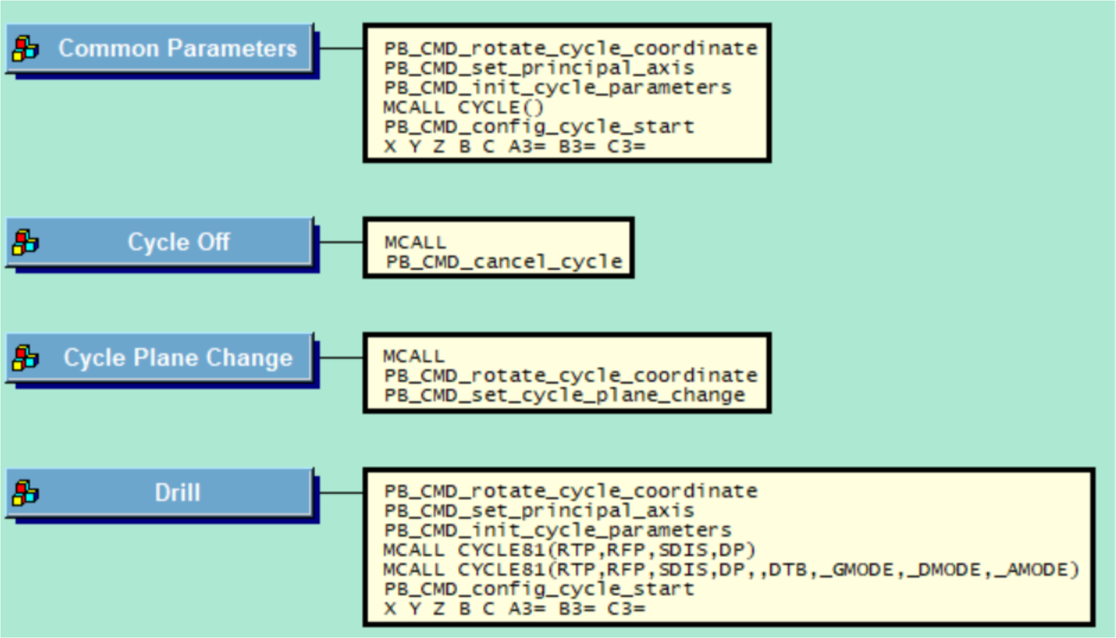
---

[17] cf. IIM TU Darmstadt, (2015a), Online-source [24.06.2020].
[18] cf. IIM TU Darmstadt, (2015p), Online-source [24.06.2020].
[19] cf. Siemens PLM Software, (2018).
[20] cf. PROLIM, (2012), Online-source [24.06.2020].
[21] cf. Akerboom, (2008), Online-source [24.06.2020].
[22] cf. Siemens PLM Software, (2009).



```
SUPA G0 X=_X_HOME...
;Tool Change
T=\"$mom_tool_nam...
M6
MSG(\"$mom_oper_m...
TRAFOOF
SUPA G0 Z=_Z_HOME...
SUPA G0 X=_X_HOME...
```

Figure 55.: Extract from Post Builder settings of the Auto Tool Change
Source: Own illustration.



Common Parameters

```
PB_CMD_rotate_cycle_coordinate
PB_CMD_set_principal_axis
PB_CMD_init_cycle_parameters
MCALL CYCLE()
PB_CMD_config_cycle_start
X Y Z B C A3= B3= C3=
```

Cycle Off

```
MCALL
PB_CMD_cancel_cycle
```

Cycle Plane Change

```
MCALL
PB_CMD_rotate_cycle_coordinate
PB_CMD_set_cycle_plane_change
```

Drill

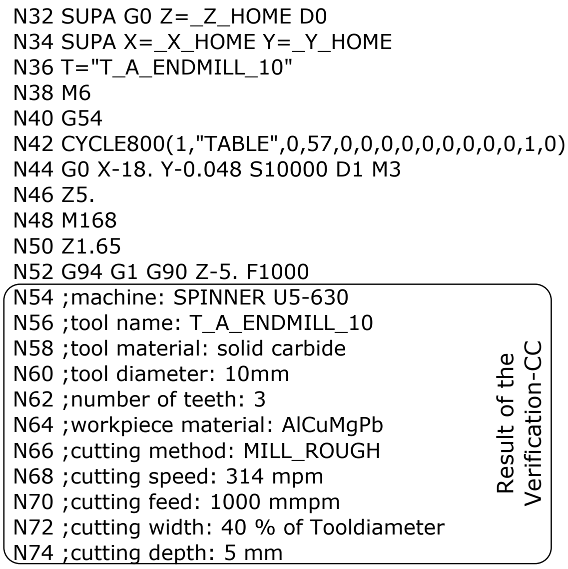
```
PB_CMD_rotate_cycle_coordinate
PB_CMD_set_principal_axis
PB_CMD_init_cycle_parameters
MCALL CYCLE81(RTP,RFP,SDIS,DP)
MCALL CYCLE81(RTP,RFP,SDIS,DP,,DTB,_GMODE,_DMODE,_AMODE)
PB_CMD_config_cycle_start
X Y Z B C A3= B3= C3=
```

Figure 56.: Extract from Post Builder settings of different cycles
Source: Own illustration.

5.2.4.1. Programmed Custom-Command for a Verification of the Used Machining Data

The fundamental problem with NC codes is that values, such as the cutting width, are available in implicit form. In order to enable the MDL parameters to be checked, they must be added in explicit form, as shown in Figure 57. These values are added as comments so that the real machine tool is not influenced in the processing of the NC code. These comments can be read in and processed by the tool described in Section 5.5.

The entire CC is shown in Figure 58. All variables used must first be defined with the "global" command. The values of the variables are transferred using the "MOM_output_literal" command. The CC, as well as the CC explained below, are placed as an independent function block at the start of each operation sequence, as shown in Figure 59. [23]



```
N32 SUPA G0 Z=_Z_HOME D0
N34 SUPA X=_X_HOME Y=_Y_HOME
N36 T="T_A_ENDMILL_10"
N38 M6
N40 G54
N42 CYCLE800(1,"TABLE",0,57,0,0,0,0,0,0,0,0,0,1,0)
N44 G0 X-18. Y-0.048 S10000 D1 M3
N46 Z5.
N48 M168
N50 Z1.65
N52 G94 G1 G90 Z-5. F1000
N54 ;machine: SPINNER U5-630
N56 ;tool name: T_A_ENDMILL_10
N58 ;tool material: solid carbide
N60 ;tool diameter: 10mm
N62 ;number of teeth: 3
N64 ;workpiece material: AlCuMgPb
N66 ;cutting method: MILL_ROUGH
N68 ;cutting speed: 314 mpm
N70 ;cutting feed: 1000 mmpm
N72 ;cutting width: 40 % of Tooldiameter
N74 ;cutting depth: 5 mm
```

Figure 57.: Example of the results of the verification-custom-command
Source: Schmid et al. (2020b).

---

[23] cf. Siemens PLM Software, (2009).

```
Proc PB_CMD_verification_custom_command_machining_data {} {
global mom_machine_name
global mom_tool_name
global mom_tool_material_description
global mom_tool_diameter
global mom_tool_flutes_number
global mom_part_material_description
global mom_oper_method
global mom_surface_speed
global mom_feed_rate
global mom_stepover_distance
global mom_depth_per_cut

MOM_output_literal ";machine: $mom_machine_name"
MOM_output_literal ";tool name: $mom_tool_name"
MOM_output_literal ";tool material: $mom_tool_material_description"
MOM_output_literal ";tool diameter: $mom_tool_diameter mm"
MOM_output_literal ";number of teeth: $mom_tool_flutes_number"
MOM_output_literal ";workpiece material: $mom_part_material_description"
MOM_output_literal ";method: $mom_oper_method"
MOM_output_literal ";cutting speed: $mom_surface_speed mpm"
MOM_output_literal ";cutting feed: $mom_feed_rate mmpm"
MOM_output_literal ";cutting width: $mom_stepover_distance % of Tooldiameter"
MOM_output_literal ";cutting depth: $mom_depth_per_cut mm" }
```

Figure 58.: Verification-custom-command
Source: Own illustration.

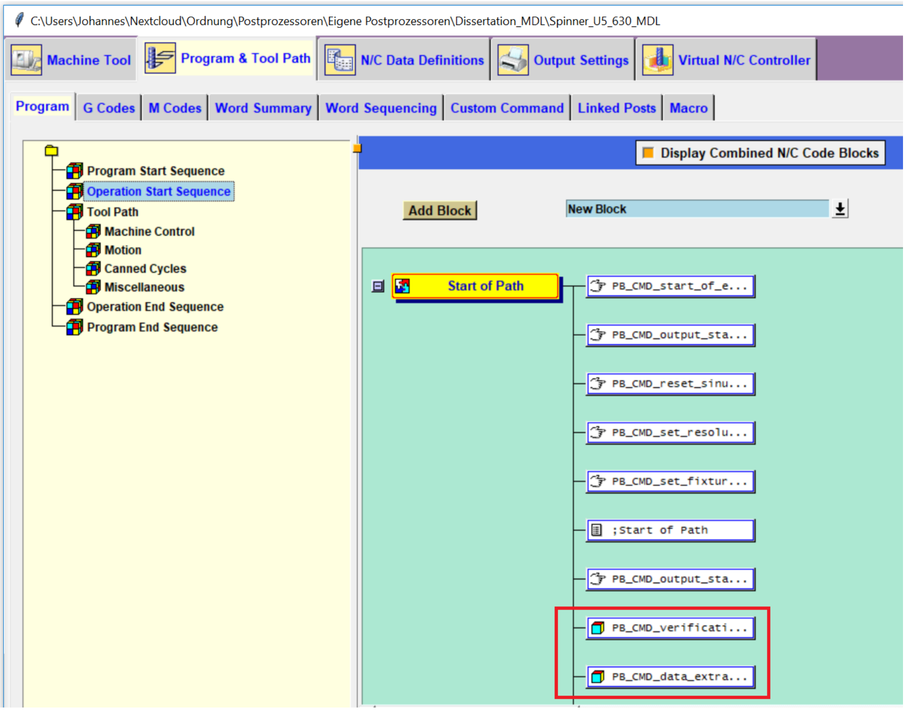
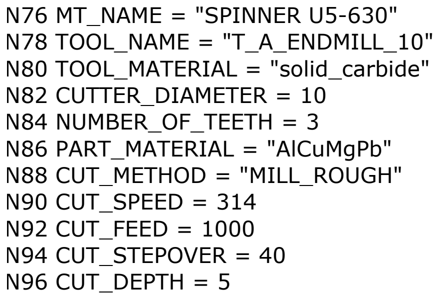


Figure 59.: Placement of both custom-commands within the post-processor structure
Source: Own illustration.

5.2.4.2. Programmed Custom-Command for a Subsequent Data Extraction from the Machine Tool

The existing problem is that either only "TARGET machine data" or "ACTUAL machine data" can be read out. A time-synchronous combination of the two types of data could only be read out indirectly. The saving of the required TARGET machine data in global variables created on the real machine tool, as shown in Figure 60, has proven to be a successful approach. The CC for the saving process is very similar to the Verification-CC and shown in Figure 61. These necessary global variables must be created manually once on the real machine tool, which is described in Section 5.3.

Then the values of the created global variables, which contain the TARGET machine data, can be read out with the ACTUAL machine data. A reliable method has been found to be that the TARGET machine data are written within the start sequence of every machining operation. The read-out process is explained in Subsection 5.4.1 in more detail.



```
N76 MT_NAME = "SPINNER U5-630"
N78 TOOL_NAME = "T_A_ENDMILL_10"
N80 TOOL_MATERIAL = "solid_carbide"
N82 CUTTER_DIAMETER = 10
N84 NUMBER_OF_TEETH = 3
N86 PART_MATERIAL = "AlCuMgPb"
N88 CUT_METHOD = "MILL_ROUGH"
N90 CUT_SPEED = 314
N92 CUT_FEED = 1000
N94 CUT_STEPOVER = 40
N96 CUT_DEPTH = 5
```

Figure 60.: Results of the data-extraction-custom-command
Source: Own illustration.

```
Proc PB_CMD_data_extraction_custom_command_machining_data {} {
global mom_machine_name
global mom_tool_name
global mom_tool_material_description
global mom_tool_diameter
global mom_tool_flutes_number
global mom_part_material_description
global mom_oper_method
global mom_surface_speed
global mom_feed_rate
global mom_stepover_distance
global mom_depth_per_cut

MOM_output_literal "MT_NAME = $mom_machine_name"
MOM_output_literal "TOOL_NAME = $mom_tool_name"
MOM_output_literal "TOOL_MATERIAL = $mom_tool_material_description"
MOM_output_literal "CUTTER_DIAMETER = $mom_tool_diameter"
MOM_output_literal "NUMBER_OF_TEETH = $mom_tool_flutes_number"
MOM_output_literal "PART_MATERIAL = $mom_part_material_description"
MOM_output_literal "CUT_METHOD = $mom_oper_method"
MOM_output_literal "CUT_SPEED = $mom_surface_speed"
MOM_output_literal "CUT_FEED = $mom_feed_rate"
MOM_output_literal "CUT_STEPOVER = $mom_stepover_distance"
MOM_output_literal "CUT_DEPTH = $mom_depth_per_cut" }
```

Figure 61.: Data-extraction-custom-command
Source: Own illustration.

5.2.5. Emulated Control via Common Simulation Engine

The creation of the required files for an emulated control of a machine tool via Common Simulation Engine (CSE) is described in the subsections below. In addition to the experimental creation of the required files, the role of the CSE between the use cases of an emulated control and a simulated control is discussed. [24]

5.2.5.1. Generation of the Required Files for an Emulated Control

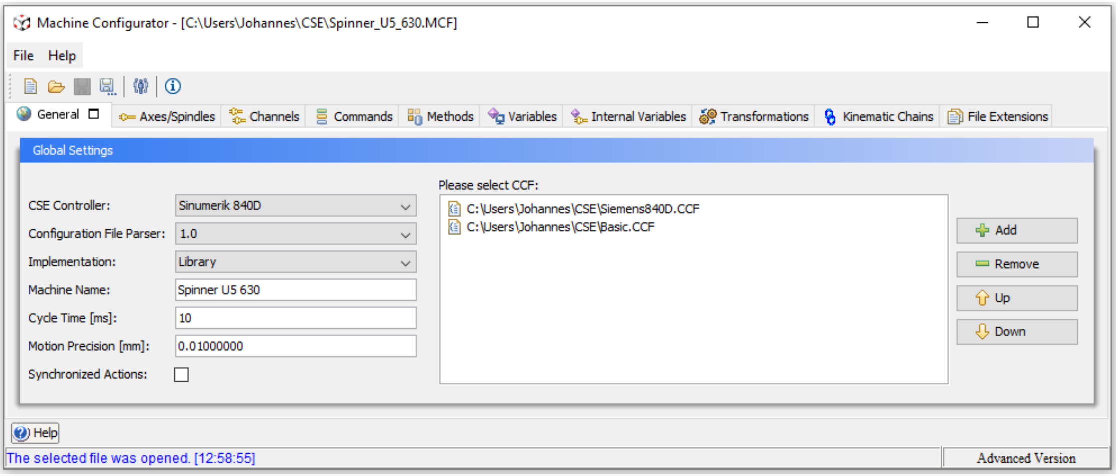
The following two types of files are required for the CSE:

- Controller configuration file (*.ccf)
- Machine configuration file (*.mcf)

---

[24] cf. Siemens, (2017a-l), Online-source [07.02.2020]

The *.ccf file is made available by the manufacturer of the respective control and contains information about the control. The *.mcf file, which contains the information about the machine tool, must be created for the respective machine tool. The software Machine Configurator is used to create this file. As shown in Figure 62, a control to be used has to be selected from a library. Then a suitable *.ccf file must be linked, as shown. After this step, all axes and spindles have to be added as shown in Figure 63. The required values of the individual axes must be entered. These values can be extracted from a commissioning archive file as mentioned previously. If a CAM simulation with emulated control is used, these values are used to calculate the processing times and those of the kinematic model, as shown in Figure 52, are overwritten. [25,26]


Machine Configurator - [C:\Users\Johannes\CSE\Spinner_U5_630.MCF]

CSE Controller: Sinumerik 840D
Configuration File Parser: 1.0
Implementation: Library
Machine Name: Spinner U5 630
Cycle Time [ms]: 10
Motion Precision [mm]: 0.01000000
Synchronized Actions: ☐

Please select CCF:
C:\Users\Johannes\CSE\Siemens840D.CCF
C:\Users\Johannes\CSE\Basic.CCF

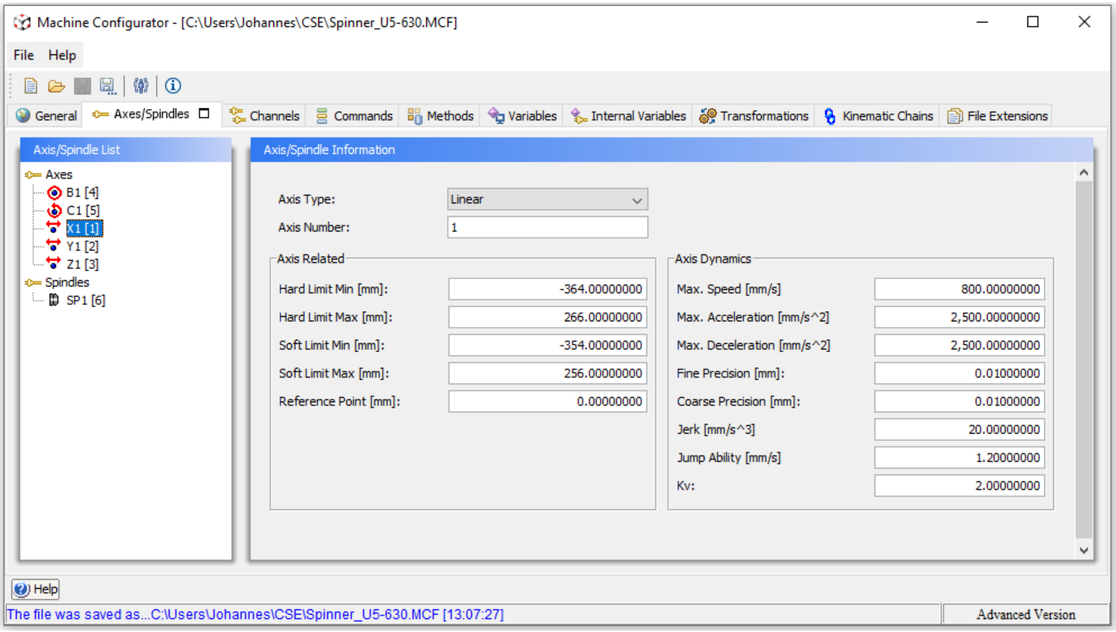
The selected file was opened. [12:58:55]

Figure 62.: Home screen of the software Machine Configurator
Source: Own illustration.

The respective G- and M-commands must be defined so that the kinematic model of the machine tool can be controlled by an NC code. The commands must first be created and then linked with internal commands. This must be done via XML, based on a defined sequence. This sequence is listed in the associated manual and must be adapted to the desired parameters. In addition to linking commands via XML, there is also the option of calling a subprogram. This is used for example for the tool change command M6. When the command is executed, an internal routine runs on the real machine tool, which executes some movements, like the movement of the door of the magazine or the tool gripper. As explained in the following subsection, this can also be represented with the DM of a machine tool. [27,28]

---

[25] cf. Siemens, (2019b), Online-source [07.02.2020].
[26] cf. Siemens, (2019a), Online-source [07.02.2020].
[27] cf. Siemens, (2019d-s), Online-source [07.02.2020]
[28] cf. Siemens, (2018a-o), Online-source [07.02.2020]



Axis Type: Linear
Axis Number: 1

Hard Limit Min [mm]: -364.00000000
Hard Limit Max [mm]: 266.00000000
Soft Limit Min [mm]: -354.00000000
Soft Limit Max [mm]: 256.00000000
Reference Point [mm]: 0.00000000

Max. Speed [mm/s] 800.00000000
Max. Acceleration [mm/s^2] 2,500.00000000
Max. Deceleration [mm/s^2] 2,500.00000000
Fine Precision [mm]: 0.01000000
Coarse Precision [mm]: 0.01000000
Jerk [mm/s^3] 20.00000000
Jump Ability [mm/s] 1.20000000
Kv: 2.00000000

The file was saved as...C:\Users\Johannes\CSE\Spinner_U5-630.MCF [13:07:27]

Figure 63.: Definition of different axes in the software Machine Configurator
Source: Own illustration.

5.2.5.2. Role of the Common Simulation Engine in a Simulated Control

Within a simulated control a subprogram is also called via an *.mcf file of an emulated control. The *.mcf file required for this is empty except for the commands for calling the subprogram. The creation of such a subprogram call is described using the example of the tool change command M6. There are two different ways to enable a virtual tool change:

Within the simple variant, the DM of the machine tool moves to the tool change point and the tool to be replaced disappears and the new one appears. This variant is installed with a standard installation of Siemens NX. The second variant includes the exact movements of the gripper and magazine door. The required data are extracted from a commissioning archive and have to be adapted to the naming of the kinematic model. In addition to the tool change, this method can also be used to control the main door of the DM of the machine tool. [29,30,31,32]

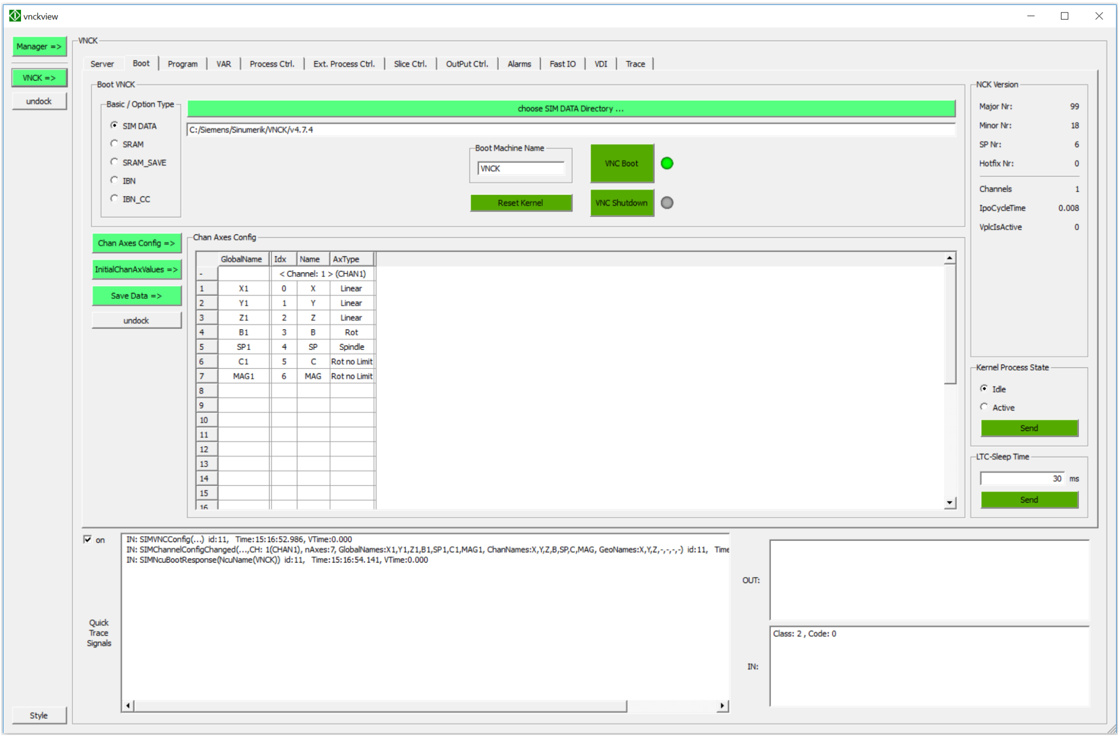
---

[29] cf. Siemens, (2018b), Online-source [07.02.2020].
[30] cf. Siemens, (2019q), Online-source [07.02.2020].
[31] cf. Siemens, (2019p), Online-source [07.02.2020].
[32] cf. Siemens, (2019m), Online-source [07.02.2020].

5.2.6. Simulated Control via Virtual Numerical Control Kernel

In addition to the emulation of a control of a machine tool, there is also the possibility of a complete simulation via Virtual NC Kernel (VNCK). The required file for such a simulation is a Static-Random-Access-Memory (SRAM) file. The software VNCKView (Home screen is shown in Figure 64) is used to create this SRAM file. This software is not intended to be used by end-customers. Accordingly, there is no manual or literature source that has dealt with this topic so far. Siemens supervised the use of this software for the present thesis.

To create a SRAM file, a commissioning archive must be read-in by using VNCKView. Then a control can be started in Operate - window mode (Figure 65a serves as an example). The simulated control that has started shows the exact status of the real control at the time the commissioning archive was created. As shown in Figures 65b, 65c and 65d, all tools, offsets and programs that were loaded by the commissioning archive must be deleted, since this data will be used in the future by the CAM application. Basically, these are the steps necessary to create the SRAM file. During the generation, however, some problems appeared, which could only be solved by experts from Siemens and are not considered in this work.



Basic / Option Type
● SIM DATA
○ SRAM
○ SRAM_SAVE
○ IBN
○ IBN_CC

C:/Siemens/Sinumerik/VNCK/v4.7.4

Boot Machine Name: VNCK

NCK Version
Major Nr: 99
Minor Nr: 18
SP Nr: 6
Hotfix Nr: 0
Channels 1
IpoCycleTime 0.008
VplcIsActive 0

	GlobalName	Idx	Name	AxType
-		< Channel: 1 > (CHAN1)		
1	X1	0	X	Linear
2	Y1	1	Y	Linear
3	Z1	2	Z	Linear
4	B1	3	B	Rot
5	SP1	4	SP	Spindle
6	C1	5	C	Rot no Limit
7	MAG1	6	MAG	Rot no Limit
8				
9				
10				
11				
12				
13				
14				
15				
16				

Kernel Process State: ● Idle ○ Active

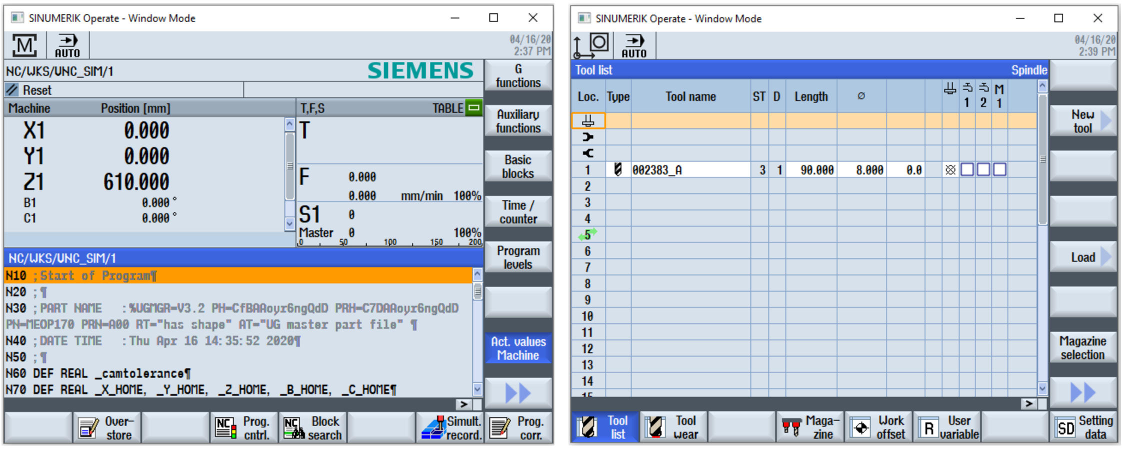
LTC-Sleep Time: 30 ms

☑ on

```
IN: SIMVNCConfig(...)  id:11,   Time:15:16:52.986, VTime:0.000
IN: SIMChannelConfigChanged(...,CH: 1(CHAN1), nAxes:7, GlobalNames:X1,Y1,Z1,B1,SP1,C1,MAG1, ChanNames:X,Y,Z,B,SP,C,MAG, GeoNames:X,Y,Z,-,-,-,-)  id:11,   Time
IN: SIMNcuBootResponse(NcuName(VNCK))  id:11,   Time:15:16:54.141, VTime:0.000
```

IN: Class: 2 , Code: 0

Figure 64.: Home screen of VNCKView after loading a commissioning archive
Source: Own illustration.



NC/WKS/UNC_SIM/1

Machine	Position [mm]
X1	0.000
Y1	0.000
Z1	610.000
B1	0.000 °
C1	0.000 °

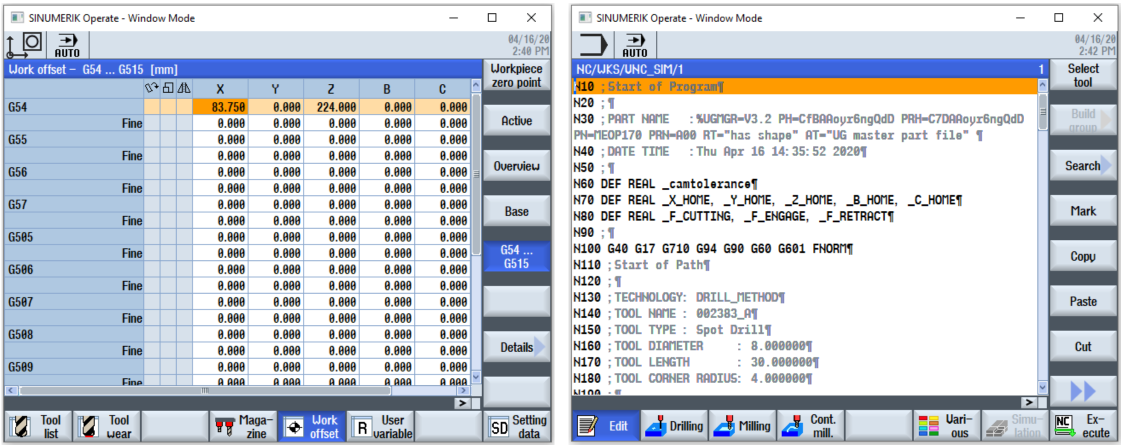
T,F,S TABLE
T
F 0.000
0.000 mm/min 100%
S1 0
Master 0 100%

NC/WKS/UNC_SIM/1

```
N10 ;Start of Program¶
N20 ;¶
N30 ;PART NAME   :%UGMGR=V3.2 PH=CfBAAoyr6ngQdD PRH=C7DAAoyr6ngQdD
PN=MEOP170 PRN=A00 RT="has shape" AT="UG master part file" ¶
N40 ;DATE TIME   :Thu Apr 16 14:35:52 2020¶
N50 ;¶
N60 DEF REAL _camtolerance¶
N70 DEF REAL _X_HOME, _Y_HOME, _Z_HOME, _B_HOME, _C_HOME¶
```

Loc.	Type	Tool name	ST	D	Length	⌀			1	2	M 1
1		002383_A	3	1	90.000	8.000	0.0	⊗	☐	☐	☐
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											

(a) Sinumerik home screen (b) Tools to be deleted



Work offset – G54 ... G515 [mm]

				X	Y	Z	B	C
G54				83.750	0.000	224.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G55				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G56				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G57				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G505				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G506				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G507				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G508				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000
G509				0.000	0.000	0.000	0.000	0.000
Fine				0.000	0.000	0.000	0.000	0.000

NC/WKS/UNC_SIM/1

```
N10 ;Start of Program¶
N20 ;¶
N30 ;PART NAME   :%UGMGR=V3.2 PH=CfBAAoyr6ngQdD PRH=C7DAAoyr6ngQdD
PN=MEOP170 PRN=A00 RT="has shape" AT="UG master part file" ¶
N40 ;DATE TIME   :Thu Apr 16 14:35:52 2020¶
N50 ;¶
N60 DEF REAL _camtolerance¶
N70 DEF REAL _X_HOME, _Y_HOME, _Z_HOME, _B_HOME, _C_HOME¶
N80 DEF REAL _F_CUTTING, _F_ENGAGE, _F_RETRACT¶
N90 ;¶
N100 G40 G17 G710 G94 G90 G60 G601 FNORM¶
N110 ;Start of Path¶
N120 ;¶
N130 ;TECHNOLOGY: DRILL_METHOD¶
N140 ;TOOL NAME : 002383_A¶
N150 ;TOOL TYPE : Spot Drill¶
N160 ;TOOL DIAMETER      : 8.000000¶
N170 ;TOOL LENGTH        : 30.000000¶
N180 ;TOOL CORNER RADIUS: 4.000000¶
```

(c) Offsets to be deleted (d) Programs to be deleted

Figure 65.: Sinumerik Operate - window mode
Source: Own illustration.

5.2.7. Linking the Individual Files of the Digital Model

After the successful creation of the kinematic model, PP, CSE and VNCK, the individual files must be linked. This is done by using a very simple *.dat file, in which the storage locations of the files to be linked must be specified. After the location of the *.dat file has been transferred to Siemens NX, the DM can be used for CAM planning. [33,34,35]

---

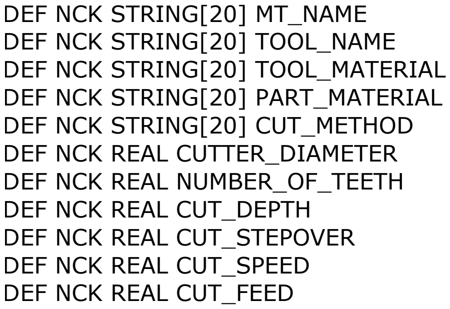
[33] cf. IIM TU Darmstadt, (2015l).
[34] cf. Siemens, (2018f), Online-source [07.02.2020].
[35] cf. Siemens, (2018d), Online-source [07.02.2020].

5.2.8. Generation of a Template-Based CAM Automation

After the DM has been successfully created, the next step is to design a suitable template. The generation of such a template does not really differ from normal CAM planning. After a CAM set-up has been created satisfactorily, it can be saved as a template. [36,37]

5.3. Adaptation of the Global User Variables of the Machine Tool

In order to save variables of the data type "string" and then read them out again via OPC UA, variables of the type "Global User Data" (GUD) must be created on the real machine tool. To achieve this, a special file must be rewritten on the control, which can be found under this path:
"System data / NC data / Definitions / UGUD.DEF"
This file must be expanded with the code shown in Figure 66 in order to create the variables. The DEF command is used to define a new variable. The command NCK describes the variable as "NC global user variable" and the next one determines the data type. A maximum length must be assigned for variables of the type "string", which in this case is 20. The name of the variable must be assigned to the last entry. It is highly important that the name is not separated by a space. [38]



```
DEF NCK STRING[20] MT_NAME
DEF NCK STRING[20] TOOL_NAME
DEF NCK STRING[20] TOOL_MATERIAL
DEF NCK STRING[20] PART_MATERIAL
DEF NCK STRING[20] CUT_METHOD
DEF NCK REAL CUTTER_DIAMETER
DEF NCK REAL NUMBER_OF_TEETH
DEF NCK REAL CUT_DEPTH
DEF NCK REAL CUT_STEPOVER
DEF NCK REAL CUT_SPEED
DEF NCK REAL CUT_FEED
```

Figure 66.: Adapted Global User Variables
Source: Own illustration.

---

[36] cf. Siemens, (2018m), Online-source [07.02.2020].
[37] cf. IIM TU Darmstadt, (2015b-m), Online-source [10.08.2020]
[38] cf. Siemens Industry Online Support, (2010), Online-source [10.08.2020].

5.4. Acquisition of Validated Machining Data

The adaptation of the PP described above made it possible to transfer the required TARGET data to the machine tool. This data can now be read out with the ACTUAL data using the next process step "13. Validated Machining Data", as marked in Figure 48, which is divided into the following sections:

- Extraction of validated machining data from a machine tool
- Evaluation of the extracted data
- Automated storage of machining data in a database

5.4.1. Extraction of Validated Machining Data from a Machine Tool

In the course of this thesis the attempt is made to generate only necessary data. For this reason, a method has been developed to read out previously selected data at a defined point in time. With regard to the machining data, these data are the previously saved TARGET data and selected ACTUAL data of cutting speed and feed. These ACTUAL values have been selected because they can most easily be influenced by a machine tool operator by using the override potentiometer. In order to speak of "validated", as in the standard mentioned above, given goals must be achieved. In this example the machine tool operator works as a human sensor. The machine tool operator has the possibility to adjust speed and feed and when the machine tool operator is satisfied with the result, the values are considered as validated. The end sequence of every machining operation is selected as the respective point in time of the readout process. This point in time is marked by switching an R-parameter by the PP.

The read-out process is then carried out via OPC UA. The data is then saved in tabular form as a *.csv file. The required application was programmed as a console application in C++ using Visual Studio with the open62541 extension within a supervised master thesis. [39]

---

[39] cf. Vallant, (2020).

5.4.2. Evaluation of the Extracted Data

The form and content of the previously generated *.csv file must be edited for subsequent steps. The TARGET and ACTUAL values of speed and feed of every operation must be compared and resulting values, which can be saved, must be determined. For this to be implemented, certain rules must be introduced. As mentioned in the subsection above, machining data can be regarded as validated when the respective machine tool operator is satisfied with the result. A major problem with this method arises if different machine tool operators use different settings in speed and feed. Another problem is the fact that tool wear also results in different values of an optimum of speed and feed. In general, the one and only correct data-set of machining data does not exist, but for the correct use of an MDL, one data-set must be chosen. In order to maintain an overview in a database, not every combination considered to be validated is automatically forwarded. Only if there is a specific number of entries of different speeds and feeds for one and the same data record, this data-set can be considered to get forwarded into the MDL. With regard to an optimized use of the machining data, the approach of "Cost-optimized tool life" was used and implemented as a Visual Basic for Applications (VBA) macro within a supervised bachelor thesis. This macro generates a suitable *.csv file, which can be loaded into the MDL by a developed application, which is described in the following subsection. [40]

5.4.3. Automated Storage of Machining Data in a Database

The functionality of the MDL appears to be insufficient concerning the developments described above. For this reason, two applications in the form of console applications were developed. **Application 1** is a simple tool that can delete all entries in the MDL. Previously, this has to be done individually for each entry. Since these required several clicks per entry and an MDL can quickly be filled with over 1000 entries, this is a very useful extension. **Application 2** enables the data to be read in from the previously generated *.csv file. A security check was added to this function, which checks all attributes except for cutting width, -depth, -speed and -feed, and whether these have previously been noted in the database. Since the NC code is only a text file, a subsequent typing error cannot be ruled out, but this method prevents it from being transferred to the database. Both applications have been programmed by professional programmers from Siemens due to the cooperation in line with the present thesis.

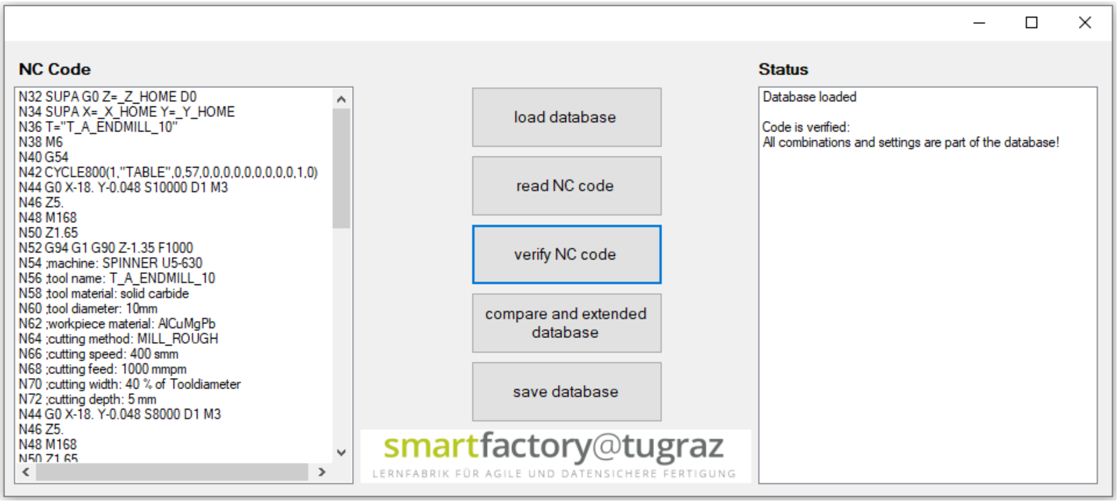
---

[40] cf. Rockenschaub, (2021).

5.5. Verification of Machining Data of New NC Codes

As already mentioned in previous sections of this work, the choice of machining data has to be classified as critical. If there are too few values in the MDL, an incorrectly interpolated combination may be passed on. If this happens, no warning is issued. Even if the CAM operator has to check the values explicitly, errors, as shown above using the PFMEA, cannot be excluded. For this reason, an application has been developed, which enables the selected machining data to be checked. With this application, generated NC code can be read in and the respective machining data can be compared with those in the database. If the machining data used are within a previously determined range of those in the database, they can be regarded as verified. The application shown in Figure 67, was created by means of a supervised project. A short description of the functions can be given as follows: [41]

- **load database: Database with previously saved values is loaded.**
- **read NC code: NC code with machining data to be checked is read in.**
- **verify NC code: Machining data are compared and a message is issued.**
- **compare and extend database: Expanding the database is possible.**
- **save database: Database can be saved after the extension.**



```
N32 SUPA G0 Z=_Z_HOME D0
N34 SUPA X=_X_HOME Y=_Y_HOME
N36 T="T_A_ENDMILL_10"
N38 M6
N40 G54
N42 CYCLE800(1,"TABLE",0,57,0,0,0,0,0,0,0,0,0,1,0)
N44 G0 X-18. Y-0.048 S10000 D1 M3
N46 Z5.
N48 M168
N50 Z1.65
N52 G94 G1 G90 Z-1.35 F1000
N54 ;machine: SPINNER U5-630
N56 ;tool name: T_A_ENDMILL_10
N58 ;tool material: solid carbide
N60 ;tool diameter: 10mm
N62 ;workpiece material: AlCuMgPb
N64 ;cutting method: MILL_ROUGH
N66 ;cutting speed: 400 smm
N68 ;cutting feed: 1000 mmpm
N70 ;cutting width: 40 % of Tooldiameter
N72 ;cutting depth: 5 mm
N44 G0 X-18. Y-0.048 S8000 D1 M3
N46 Z5.
N48 M168
N50 Z1.65
```

```
Database loaded

Code is verified:
All combinations and settings are part of the database!
```

Figure 67.: Verification of machining data of new NC codes
Source: Schmid et al. (2020a).

---

[41] cf. Schmid et al., (2020a).

5.6. Automatic Preparation of Scanned Tools for CAM Application

Complete tools that have been 3D-scanned using a presetting and measuring machine can be saved in various file formats. The *.dxf format appears to be the most promising. Figure 68 (black contour) shows a sample result of this scanning process. For the use in a CAM software, digital tools must be set-up as precisely as necessary and as simply as possible. For this reason, the scanned contour of the tool holder is automatically replaced with a simplified one. This simplified contour is chosen larger for safety reasons, as shown in red in Figure 68. Then a parameterization is carried out according to a defined pattern. This enables certain parameters to be automatically transferred into a tabular form that describes the components. Since the section of the end mill that is covered by the holder can not be seen in the scan, it can only be estimated. For this reason, the parameters of the respective components must subsequently be checked by the user. In order to comply with the principle of the TMS used, to assemble individual components into complete tools, the scanned complete tool must be separated into its individual components. In order to achieve this, the parameters previously put in tabular form are broken down according to their affiliation.

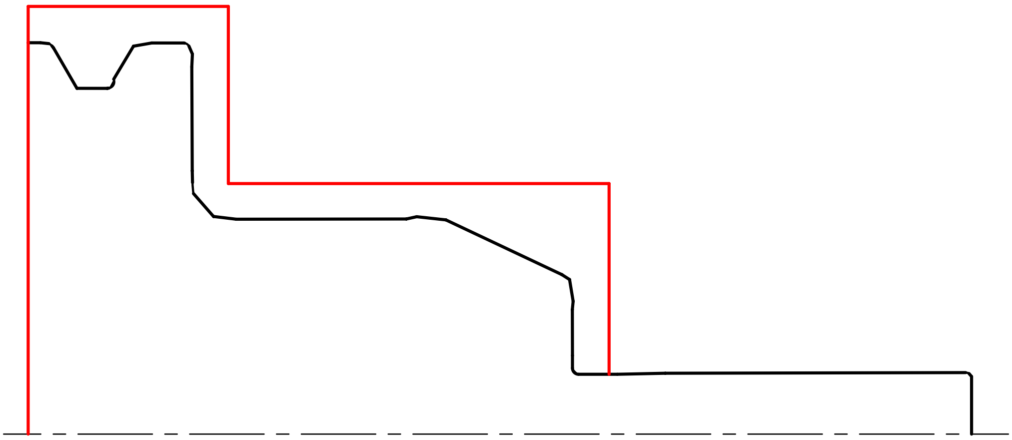


Figure 68.: 3D-scanned complete tool (black) and simplified tool holder (red)
Source: Own illustration.

Table 22 shows, for example, the associated numerical values of the principle of a milling cutter, as depicted in Figure 69. The columns of the whole table are linked with the classified attributes of the TMS. This enables an automatic data transfer to the TMS database. The transferred data can then be used within the TMS to create associated CAD data. Figure 70 shows the generated CAD data from the previously described example of a milling cutter. The advantage of this method is that the probability of an incorrectly generated tool component is significantly reduced. In addition, the time required to create a component has been reduced many times over. All of these steps were automated using the NXopen extension of Siemens NX, which was carried out within a supervised master's thesis. [42]

Table 22.: Classification attributes of a milling cutter
Source: Own illustration.

DC	DN	APMX	LPR	OAL	LH	DMM	LS	RE	CHW	KCH	AZ
10	9.7	22	52	72	30	10	40	0	0	0	0

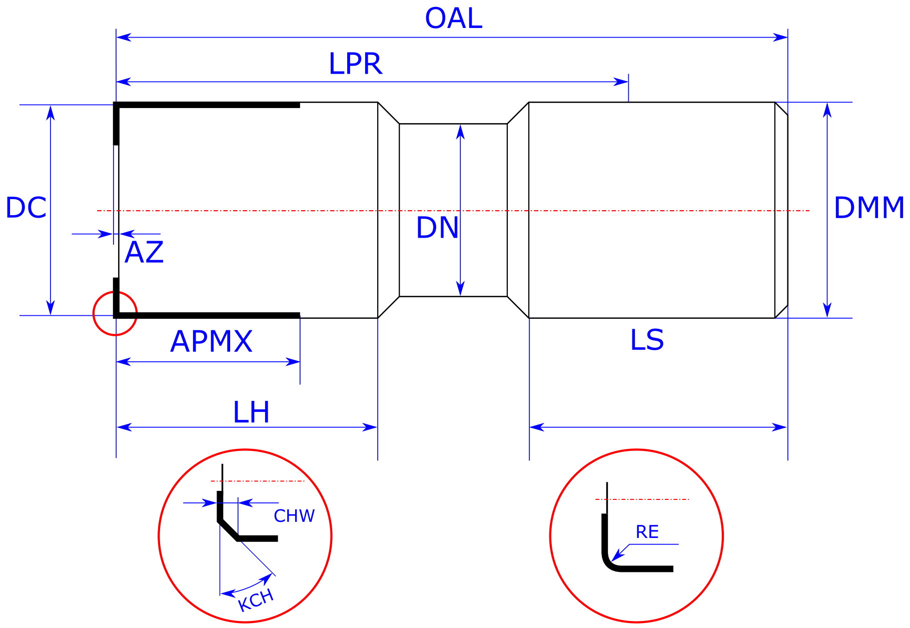
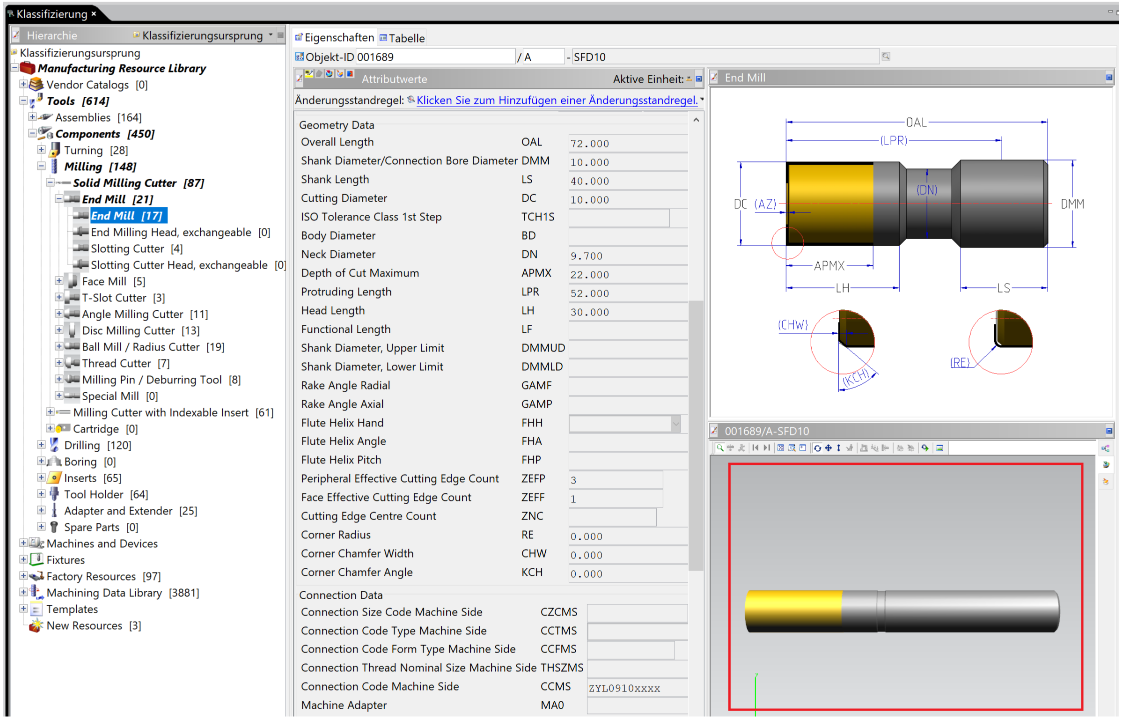


Figure 69.: Classification attributes of a milling cutter
Source: Müller (2021).

---

[42] cf. Müller, (2021).



- Klassifizierungsursprung
  - ***Manufacturing Resource Library***
    - Vendor Catalogs [0]
    - ***Tools [614]***
      - Assemblies [164]
      - ***Components [450]***
        - Turning [28]
        - ***Milling [148]***
          - ***Solid Milling Cutter [87]***
            - ***End Mill [21]***
              - ***End Mill [17]***
              - End Milling Head, exchangeable [0]
              - Slotting Cutter [4]
              - Slotting Cutter Head, exchangeable [0]
            - Face Mill [5]
            - T-Slot Cutter [3]
            - Angle Milling Cutter [11]
            - Disc Milling Cutter [13]
            - Ball Mill / Radius Cutter [19]
            - Thread Cutter [7]
            - Milling Pin / Deburring Tool [8]
            - Special Mill [0]
          - Milling Cutter with Indexable Insert [61]
          - Cartridge [0]
        - Drilling [120]
        - Boring [0]
        - Inserts [65]
        - Tool Holder [64]
        - Adapter and Extender [25]
        - Spare Parts [0]
    - Machines and Devices
    - Fixtures
    - Factory Resources [97]
    - Machining Data Library [3881]
    - Templates
    - New Resources [3]

Objekt-ID 001689 / A - SFD10

Änderungsstandregel: Klicken Sie zum Hinzufügen einer Änderungsstandregel.

Geometry Data

Overall Length	OAL	72.000
Shank Diameter/Connection Bore Diameter	DMM	10.000
Shank Length	LS	40.000
Cutting Diameter	DC	10.000
ISO Tolerance Class 1st Step	TCH1S	
Body Diameter	BD	
Neck Diameter	DN	9.700
Depth of Cut Maximum	APMX	22.000
Protruding Length	LPR	52.000
Head Length	LH	30.000
Functional Length	LF	
Shank Diameter, Upper Limit	DMMUD	
Shank Diameter, Lower Limit	DMMLD	
Rake Angle Radial	GAMF	
Rake Angle Axial	GAMP	
Flute Helix Hand	FHH	
Flute Helix Angle	FHA	
Flute Helix Pitch	FHP	
Peripheral Effective Cutting Edge Count	ZEFP	3
Face Effective Cutting Edge Count	ZEFF	1
Cutting Edge Centre Count	ZNC	
Corner Radius	RE	0.000
Corner Chamfer Width	CHW	0.000
Corner Chamfer Angle	KCH	0.000

Connection Data

Connection Size Code Machine Side	CZCMS	
Connection Code Type Machine Side	CCTMS	
Connection Code Form Type Machine Side	CCFMS	
Connection Thread Nominal Size Machine Side	THSZMS	
Connection Code Machine Side	CCMS	ZYL0910xxxx
Machine Adapter	MA0	

Figure 70.: Automatically created component
Source: Own illustration.

5.7. Evaluation of the Implemented Solution Approaches

Within this section, an evaluation of the developed methods is done. The evaluation is divided into subsections, which correspond to the approaches of Section 5.1.

5.7.1. Closed-Loop Manufacturing for Validated Machining Data

The data transfer through the programmed Data Extraction - CC, which is explained in Subsection 5.2.4.2, can be classified as very reliable (10 of 10). This is mainly due to the fact that if previously required sections of the data record are not defined, the value 0 is transferred, which leads to an invalid data record. If an invalid data record is generated, the user is encouraged to generate a valid one using the program.

The subsequent read-out process using the method programmed in C++, as explained in Subsection 5.4.1, is classified as less reliable (7 of 10). In the course of some test runs, some performance problems have been found. The respective improvement is described in the outlook of this thesis. The method programmed using VBA for evaluating the data, as described in Subsection 5.4.2, can be classified as highly reliable (9 of 10). If an incomplete data record has been generated in spite of various security mechanisms, it can be removed within this step. This combination of methods leads to data records of very high accuracy.

The subsequent mechanism, which imports the data records into the MDL, can also be classified as very reliable (10 of 10). As already described in Subsection 5.4.3, in addition to the method for importing the data, a method for an absolute deletion of the MDL has also been developed. This indirectly supports the reliability of the import program, since in the event of errors caused by the user, a new import process can be carried out without loss of data.

5.7.2. Verification Mechanism of Machining Data of New NC Codes

The method described in Subsection 5.5 for verifying the machining data of new NC codes can be classified as very reliable (10 of 10). This mainly results in the ease of use of the application.

5.7.3. Automatic Preparation of Scanned Tools for CAM Application

The detection of the most important sections of the contour of the scanned complete tool works highly reliably as long as the tool is scanned in a clean condition (9 of 10). If the tool has been scanned in an uncleaned state, chips that are left behind, for example, can lead to a falsified scan result. Despite this fact, this methodology can be classified as very reliable, as a visual inspection by the user is planned after all important steps.

5.7.4. Risk Analysis After Improvements

In order to be able to quantitatively assess the improvements developed, a new risk analysis is carried out. All influenced values are summarized in Table 23 and reassessed. For a better overview, the changed values are shown in red and discussed in the subsequent subsections.

5.7.4.1. Tool Management Software

The developed automatic preparation of scanned tools for CAM application improves the problems described with regard to incorrectly created digital tool components. In contrast to an application without the developed method, the number of errors involved are much lower. This improvement alone has reduced the RPN from a value of 60 to 20.

5.7.4.2. MDL Software

The possibility of incorrect data being entered in the MDL is drastically reduced by the CLM approach. If an incorrect entry occurred, it could be recognized by the evaluation method. Since the probability of occurrence in this case is reduced and the possibility of detection improved, the RPN has been reduced very drastically from a value of 120 to 10.

The previously most critically rated error, which was the incorrect interpolation, has also been drastically reduced. Based on the implemented CLM approach, the probability of occurrence of too few values in the database is reduced on average. The tool developed to verify the selected values gives almost error-free feedback as to whether the chosen values are in the database or not. Because of this combination of improvements, the RPN has been reduced from 210 to 20.

5.7.4.3. CAM Software

Within this element, an error that can be assigned to incorrect machining data was also rated critically. The CLM approach and the verification tool has reduced the value of the RPN from 126 to 14 and from 180 to 20.

Table 23.: PFMEA - Risk Analysis after improvements

Source: Own illustration.

Nr.	**Potential failure**	**Potential effect(s) of failure**	**S**	**Potential cause(s) of failure**	**Current preventive action**	**O**	**Detective action**	**D**	**SxO**	**RPN**
Structure: Tool Management Software				**Function: Generation of tool components**						
8	Wrong geometry created	Possible collision on the real machine tool	10	Data mixed up	**Developed method**	~~3~~ **1**	CAM simulation or presetting machine	2	~~30~~ **10**	~~60~~ **20**
Structure: MDL Software				**Function: Saving of machining data**						
22	Insufficient combinations entered	CAM operator influenced by wrong values	5	Typing error	**CLM approach**	~~4~~ **1**	**Evaluation tool**	~~6~~ **2**	~~20~~ **5**	~~120~~ **10**
23	Interpolation of the data caused errors	CAM operator influenced by wrong values	5	Too few values in the database	**CLM approach**	~~7~~ **4**	**Verification tool**	~~6~~ **1**	~~35~~ **20**	~~210~~ **20**
Structure: CAM Software				**Function: Planning of the manufacturing process**						
29	Inappropriate machining data selected	Quality of the real workpiece is insufficient	7	Human error	**CLM approach**	~~3~~ **2**	**Verification tool**	~~6~~ **1**	~~21~~ **14**	~~126~~ **14**
		Possible collision on the real machine tool	10	Human error	**CLM approach**	~~3~~ **2**	**Verification tool**	~~6~~ **1**	~~30~~ **20**	~~180~~ **20**

6. Conclusion

The present thesis dealt with the topic of digitalization in the field of machine tools and tool management. The research objective of this thesis was to elaborate a state of the art CAD-CAM-CNC process chain, which should be specifically suitable for SMEs and small lot sizes up to lot size 1 production. In addition to the theoretical elaboration of this process chain, it was validated based on an actual implementation at smartfactory@tugraz, which is the Learningfactory at the Institute of Production Engineering at Graz University of Technology. Afterwards, the selected process chain was examined for specific and general problem areas, which were mastered through further developments.

6.1. Recapitulation of Topics

6.1.1. Selected CAD-CAM-CNC Process Chain

With regard to production planning, an **integrated CAD-CAM system** with a **CAM simulation with simulated control** was chosen, which is provided as a **template**. The combination of a simulated control within a CAM simulation with an integrated CAD-CAM system network turned out to be perfectly suited for lot size 1 production. The main reasons for this are the ability to quickly create CAM programs and their reliable simulation. After a finished CAM program has been saved as a template, the further effort was limited, which demonstrated the suitability for SMEs.

A **PLM system** was chosen as the recommended data management method. Basically, the introduction of such a system involves a lot of effort and therefore is only partially suitable for an SME. Nevertheless, a PLM system can initially only be used as a PDM system, which means significantly less effort. Should a PLM system be required in the future, the functionality of a PDM system may no longer be sufficient and a much more complex switch to a PLM system would be necessary. The PLM extension **SFC** was selected to transfer NC codes and associated documentation from the PLM system to the machine tools.

With regard to tool management, the type of a **TMS independent from the CAM software** in combination with a suitable **TDS** was chosen. Its major advantage is the independence from the CAM software. If the CAM software is changed in the future, the already existing tool data can still be used. Furthermore, data that have been created in the TMS can be mirrored on the TDS, which results in a reduced effort.

The use of an **MDL** was chosen as the method for managing machining data. This method seemed to be more suitable in terms of implementation effort with regard to a variance of the values when using the same tools on different machine tools. A simulation of the machining process and therefore for the machining data was not taken into account because it is not really suitable for lot size 1 production due to the fact that the respective FRF can only be determined after a physical set-up process.

The measurement on a **presetting and measuring machine** proved to be the most suitable method for measuring complete tools. The reasons for this measurement method are the high number of set-up processes associated with lot size 1 production, which would lead to high downtimes of the machine tools, if the tools were measured inside the machine tool by using a touch probe or a laser-system. The method **QR-code with self-adhesive labels** was selected for the data transfer process from the presetting and measuring machine to the machine tool. The reasons for this selection are that the data transfer method using RFID cannot be fully exploited and that manual methods are not reliable enough.

6.1.2. Maturity Model of the Selected Process Chain

As with the general selection of the components of the process chain, the sequence of the implementation depends very much on the area of application of the company. On the basis of a fictitious initial state that was considered to be suitable, a maturity model was developed which represents the various degrees of maturity of the process chain.

The following implementation sequence was developed for an SME that is a contract manufacturer (lot size 1). The maturity level 0, which contains 6 machine tools (3 lathe machine tools and 3 milling machine tools) and a CAD software that cannot be integrated, was chosen as the fictitious starting point.

- Maturity level 0: 3 lathe machine tools and 3 milling machine tools; CAD software that cannot be integrated
- Maturity level 1: CAM simulation with simulated control for milling machine tools with 5 axes, CAM simulation without consideration of the control for milling machine tools with 3 axes; TMS for the respective tools
- Maturity level 2: Presetting and measuring machine with the data transfer method QR-code with self-adhesive labels; Connection of the presetting and measuring machine with the TMS
- Maturity level 3: TDS for milling and turning tools
- Maturity level 4: CAM simulation without consideration of the control for simple lathe machine tools; CAM simulation with simulated control for complex mill-turn machine tools
- Maturity level 5: MDL
- Maturity level 6: Integrated CAD software and therefore an integrated CAD-CAM system
- Maturity level 7: PLM software used as a PDM software at the beginning

An optimal CAD-CAM-CNC process chain that is generally valid for all types of SMEs does not exist. The content and the order of implementation are very much dependent on the field of activity of the respective company. Furthermore, the optimal level of maturity is also questionable. The components up to maturity level 3 have a manageable implementation effort and a very good overall functionality. For these reasons, the solution presented in this work has to be seen as a recommendation.

6.1.3. Evaluation of the Selected Process Chain

The presented process chain was examined for sources of errors using a PFMEA. In addition, many discussions were held with experts from the industry. The content of these qualitative discussions served as the basis for the creation of a questionnaire, which is intended to quantitatively evaluate general problems with regard to digitalization in the area of machine tools and tool management.

The investigation using PFMEA revealed a very high potential for errors in the selection of suitable machining data for the machining process. The reason why this area is classified as so critical lies in the fact that incorrect machining data can lead to serious damage to a machine tool. The most striking problem is that incorrect machining data can usually not be recognized by means of a CAM software, as it is the case with collisions, for example. Databases that are used to store machining data, such as the MDL used, can reduce the frequency of errors in this case. However, it must be ensured that this database has been filled with correct values beforehand. Since this is a manual task, errors cannot be excluded. If incorrect values are entered in the MDL, these can influence the CAM operator to make an incorrect entry. A further complicating factor, which was also confirmed by the survey, is that the manufacturer's information of machining data can often not be trusted. For this reason, the machining data should first be validated on the machine tools used, which leads to a very high level of effort. If there are too few suitable values in the MDL, the values are interpolated. The interpolation works well if there are many values in the database. If the value to be interpolated deviates too far from the existing values, incorrect values can also be transferred. Another related problem is that the CAM operator is not notified if an interpolation occurs.

Another striking challenge is associated with the generation of digital tool components. If errors occur during this process, the machine tool can be severely damaged. By using the subsequent CAM simulation or by measuring the physical complete tool and comparing it with the digital one on a presetting and measuring machine, a large number of errors can be detected, but not all. An incorrect holder geometry, for example, can often not be recognized by a presetting and measuring machine. Since the geometry data loaded from the Internet cannot be trusted to be correct, the generation of the digital tool components is associated with a very high level of manual effort, in which errors cannot be ruled out.

A further source of error to be emphasized is the data transfer from a presetting and measuring machine to a machine tool. Similar to the other mentioned sources of error, the machine tool can be severely damaged if errors occur during the data transfer. The most striking problem is the fact that the respective sources of error are the manual work task of measuring and setting up the complete tools on the machine tool.

Another problem, recognized primarily through the discussion with experts from industry and the survey, is that available software products in the area of the CAD-CAM-CNC process chain are not only complicated, but also very complex. The survey also confirms that these products are available on the market in a very diverse range, which makes the development of an implementation strategy very difficult.

6.1.4. Optimization of the Selected Process Chain

The automatic filling of tool management databases was subdivided within this thesis into machining data, which are acquired through a CLM approach, and geometry data of tool components, which are generated from a 3D scan and prepared by an automated method.

Closed-Loop Manufacturing for Validated Machining Data

A CLM approach was developed to reduce the likelihood of the incorrect entry of machining data in an MDL. Machining data that are used on a machine tool under real conditions should be read out automatically and stored in an MDL after a corresponding evaluation. The major problem that had to be solved in order to enable this read-out process was that the required data was not transferred to the machine tool. This transfer was carried out with a specifically developed DM, which saves the required values of the MDL (machine tool, tool material, tool diameter, workpiece material, cutting method, cutting width, cutting depth, cutting speed and cutting feed) at the beginning of each machining operation in specifically defined variables of the machine tool. The TARGET data transferred via the DM can then be read out with the ACTUAL data via OPC UA. To make this read-out process possible, a console application was programmed in C++ with the open62541 extension. The point of time of the read-out process is placed at the end of the respective machining operation, which is indicated by switching a specific R-parameter by the associated PP. Using this application, the required data is saved in a *.csv file. The evaluation of the data takes place in an application that was programmed using VBA.

Since there are many different combinations of machining data valid for the same setting, only those which correspond to a previously defined "Cost-optimized tool life" are forwarded to the MDL. The evaluated data can then be imported into the MDL using an application programmed by experts from Siemens. The advantages of this CLM approach are that the probability of incorrectly entered machining data in an MDL is lower. Furthermore, the effort required to fill an MDL is also reduced.

Verification Mechanism of Machining Data of New NC Codes

An application was developed to eliminate the problem of a possible incorrect interpolation without notification, as described above. This application enables the machining data used to be compared with those in the MDL and then outputs a message. The combination of the aforementioned CLM approach with the verification mechanism results in a very reliable selection method for machining data. However, this method is not absolutely free of errors. The machining process is very complex and can not only be described by the parameters used in the MDL. There are always exceptional situations that might often cause other conditions. For example, the machining behavior of a tool is not the same throughout its lifetime. For reasons like this, expert knowledge will always be necessary.

Automatic Preparation of Scanned Tools for CAM Application

The starting point for this method is a 3D scan of a complete tool using a presetting and measuring machine. The scanned complete tool is broken down into its components and described by parametric sketches by an automated method, which was programmed using NXopen. The respective values of the characteristic dimensions are rounded to the nominal dimension and visualized for the user to check. The components then can be saved and loaded into a tool management database. By means of this automated method for generating digital tool components, on the one hand the high effort of creating a tool management database should be reduced and on the other hand possible sources of error should be limited. Because of the fact that the user can carry out a visual inspection and thus intervene in the action of the developed macro, this method can be classified as very reliable as a whole and the amount of time saved by using this method is enormous.

6.2. Future Research

Closed-Loop Manufacturing for Validated Machining Data

The two CCs, which convey the necessary data in the respective NC code, were sufficient for the demonstrator in the context of this work. For a more universally applicable variant of this method, a User Defined Event (UDE) is more advisable than a CC. The advantage of an UDE is that several variants can be mapped with less programming effort. In addition, an UDE can be programmed to respond differently to different digital complete tools. This can be used, for example, to cover all tool types with one UDE.

Edge computing, for example, can be used to enable a more reliable read-out process. The data can then be saved in a cloud platform such as the MindSphere by Siemens or similar. The evaluation of the data, which was carried out within this thesis using VBA, can then be done by using a MindSphere application. These data then can be exported from the MindSphere and imported into the MDL by the developed application. Another potential for improvement would be the development of a direct connection between the MDL and the MindSphere. [1,2]

Another logical step in further development would be a general improvement of the MDL. Since the manual filling of the database was assumed as the initial situation in the development of the MDL, the parameters used were reduced to the essentials. Using the method presented in this thesis, the parameters used can be selected more widely. [3]

Verification Mechanism of Machining Data of New NC Codes

As explained in the evaluation, the presented method for verifying machining data worked very reliably. A direct integration into the CAM or MDL software used is the most obvious improvement potential. In addition, it would be advantageous to incorporate the verification mechanism directly into a shop documentation, as this could result in an automated documentation.

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[1] cf. Siemens AG, (2019a).

[2] cf. Trabesinger et al., (2020).

[3] cf. Peng et al., (2015).

Automatic Preparation of Scanned Tools for CAM Application

The developed method was implemented for the tool type of an end mill. An implementation of this method for other tool types would be desirable. Furthermore, the characteristic parameters of the generated components currently have to be manually transferred to the TMS. This should also be automated in order to save time and avoid errors. Furthermore, some parameters, such as the number of teeth or the effective cutting length, are currently only estimated and passed on to the user for checking. This can be optimized by an improved scan. Another optimization approach is the integration into a TMS, which offers the possibility of comparing data sets with others, such as Tooltracer. The data records obtained can then be compared with similar ones and any possible errors can be identified. [4]

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[4] cf. TCM International, (2021), Online-source [13.04.2021].

References

Abramovici, Michael; Göbel, Jens; Dang, Bao (2016): *Semantic data management for the development and continuous reconfiguration of smart products and systems.* CIRP Annals - Manufacturing Technology, 65:185–188.

Aggarwal, Shivani; Varghese, Irene (2017): *Advanced Imaging Algorithms in Digital Twin Reconstruction of Construction Sites.* Available from: `https://www.infosysblogs.com/finspeak/2017/03/digital_twins_manufacturing_em.html`. Last accessed on 05.02.2020.

Akerboom, Ken (2008): *Advanced Post Builder Techniques.* Available from: `https://www-cad.fnal.gov/PLMWorld2008/Manufacturing/Akerboom_advanced_post_builder%255B1%255D.pdf`. Last accessed on 24.06.2020.

Alam, Kazi Masudul; El Saddik, Abdulmotaleb (2017): *C2PS: A Digital Twin Architecture Reference Model for the Cloud-based Cyber-Physical Systems.* IEEE Access, 5:2050–2062.

Altair (2019): *Altair digital platform.* Available from: `https://www.altair.com/iot/`. Last accessed on 05.02.2020.

Altintas, Yusuf (2016): *Virtual High Performance Machining.* Procedia CIRP, 46:372–378.

Altintas, Yusuf; Kersting, P.; Biermann, Dirk; Budak, Erhan; Denkena, Berend; Lazoglu, Ismail (2014): *Virtual process systems for part machining operations.* CIRP Annals - Manufacturing Technology, 63.

Ammermann, Dirk (2017): *Digital Twins and the Internet of Things (IoT).* Available from: `https://blogs.sap.com/2017/09/09/digital-twins-and-the-internet-of-things-iot/`. Last accessed on 05.02.2020.

ANSYS (2017): *Advantage - Spotlight on the digital twin.* Available from: `https://www.ansys.com/-/media/Ansys/corporate/resourcelibrary/article/ansys-advantage-digital-twin-aa-v11-i1.pdf`. Last accessed on 05.02.2020.

Armendia, Mikel; Ghassempouri, Mani; Ozturk, Erdem; Peysson, Flavien (2019): *Twin-Control A Digital Twin Approach to Improve Machine Tools Lifecycle*. Springer.

Asimov, R.; Chernoshey, S; Kruse, I; Asipovich, Vital (2018): *DIGITAL TWIN IN THE ANALYSIS OF A BIG DATA*. Int. Sci. and Prac. Conf. BIG DATA and Adv. Anal.

Bauernhansl, Thomas (2016): *Wgp-Standpunkt Industrie 4.0*. Wissenschaftliche Gesellschaft für Produktionstechnik Wgp e. v.

Becker, Jörg; Knackstedt, Ralf; Poeppelbuss, Jens (2009): *Entwicklung von Reifegradmodellen für das IT-Management*. Wirtschaftsinformatik, 51:249–260.

Binder, Roman (2018): *Stabilitätsverhalten einer Werkzeugmaschine*. Technische Universität Graz - Institut für Mechanik.

Black, J; Kohser, R (2019): *Materials and Processes in Manufacturing*. WILEY, 13. ed.

Bosch, Eva; Metternich, Joachim (2018): *Understanding and assessing complexity in cutting tool management*. Procedia CIRP, 72:1499–1504.

Botkinaa, Darya; Hedlindb, Mikael; Olssonc, Bengt; Hensera, Jannik; Lundholma, Thomas (2018): *Digital Twin of a Cutting Tool*. Procedia CIRP, 72:215–218.

Bracht, Uwe; Geckler, Dieter; Wenzel, Sigrid (2017): *Digitale Fabrik – Methoden und Praxisbeispiele*. Springer Vieweg, 2. ed.

Brecher, Christian; Königs, Michael; Lohse, Wolfram (2013): *Ein STEP- und STEP-NC-basiertes PLM-System*. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 108:872–877.

Brecher, Christian; Weck, Manfred (2017): *Werkzeugmaschinen Fertigungssysteme 2 - Konstruktion Berechnung und messtechnische Beurteilung*. 9. ed.

Brenner, Beate; Hummel, Vera (2017): *Digital Twin as Enabler for an Innovative Digital Shopfloor Management System in the ESB Logistics Learning Factory at Reutlingen - University*. Procedia Manufacturing, 9:198–205.

Brenner, Dominik; Kleinert, Fabian; Imiela, Joachim; Westkämper, Engelbert (2017): *Life Cycle Management of Cutting Tools: Comprehensive Acquisition and Aggregation of Tool Life Data*. Procedia CIRP, 61:311–316.

Brillinger, Markus; Martinez, Juan; Schmid, Johannes (2019): *Improving CAD/CAM Process Chains in Forging Industries in the Era of Digitalization Based on a Case Study*. 121:1–7.

CAD CAM Engineering (2014): *Shop Documentation Siemens NX*. Available from: `https://cadcamengineering.net/shop-documentation-siemens-nx/`. Last accessed on 17.06.2020.

Canton, Maurizio (2017): *Doubling Efficiency with Digital Twins*. Available from: `https://www.tibco.com/blog/2017/01/30/doubling-efficiency-with-digital-twins/`. Last accessed on 05.02.2020.

Chang, Y.S., Oh, C.H.; Whang, Y.S.; Lee, J.J.; Kwon, J.A.; Kang, M.S.; Park, Jun.s; Ung, Y.P. (2006): *Development of RFID Enabled Aircraft Maintenance System*. 2006 IEEE International Conference, pp. 224 – 229.

Ciavotta, Michele; Alge, Marino; Menato, Silvia; Rovere, Diego; Pedrazzoli, Paolo (2017): *A Microservice-based Middleware for the Digital Factory*. Procedia Manufacturing, 11:931–938.

DIN 4003-1 (2017): *Konzept für den Aufbau von 3D-Modellen auf Grundlage von Merkmalen nach DIN 4000 – Teil 1: Übersicht und Grundlagen*. Deutsches Institut für Normung.

DIN EN ISO 9000 (2015): *Quality management systems — Fundamentals and vocabulary*. Deutsches Institut für Normung.

DNV-GL (2018): *Data smart asset solutions - Digital twin*. Available from: `https://www.dnvgl.com/services/data-smart-asset-solutions-digital-twin-65556`. Last accessed on 05.02.2020.

Emanuele, Dovere; Cavalieri, Sergio; Ierace, Stefano (2015): *An assessment model for the implementation of RFID in tool management*. IFAC-PapersOnLine, 48:1007–1012.

Ematinger, Reinhard (2017): *Von der Industrie 4.0 zum Geschäftsmodell 4.0: Chancen der digitalen Transformation*. Springer Gabler.

Energy 4.0 (2017): *Windanlagen bekommen Digitalen Zwilling in der Cloud*. Available from: `https://www.industr.com/de/windanlagen-bekommen-digitalen-zwilling-2313703`. Last accessed on 15.07.2020.

Erkorkmaz, Kaan; Altintas, Yusuf; Yeung, C.-H (2006): *Virtual Computer Numerical Control System*. CIRP Annals - Manufacturing Technology, 55:399–402.

Estman, L.; Merdol, Doruk; Brask, K.-G; Kalhori, Vahid; Altintas, Yusuf (2014): *Development of Machining Strategies for Aerospace Components, Using Virtual Machining Tools*, pp. 63–68.

Gittler, Thomas; Gontarz, Adam; Weiss, Lukas; Wegener, Konrad (2019): *A fundamental approach for data acquisition on machine tools as enabler for analytical Industrie 4.0 applications*. Procedia CIRP, 79:586–591.

Gockel, Brian; Tudor, Andrew; Brandyberry, Mark; Penmetsa, Ravi; Tuegel, Eric (2012): *Challenges with Structural Life Forecasting Using Realistic Mission Profiles*.

Gomeringer, Roland, Heinzler, Max, Kilgus, Roland; Menges, Volker; Näher, Friedrich; Oesterle, Stefan; Scholer, Claudius; Stephan, Andreas; Wieneke, Falko (2014): *Formeln für Metallberufe*. Europa Lehrmittel, 11. ed.

Grieves, Michael (2015): *Digital Twin: Manufacturing Excellence through Virtual Factory Replication*.

Grieves, Michael; Vickers, John (2017): *Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems*, pp. 85–113.

Haffer, Reiner, Becker-Kavan, Angelika; Boom, Gregor; Brandt, Finn; Braun, Christof; Lindner, Volker; Schulz, Elisabeth; Timm, Jochen (2017): *Grundkenntnisse Industrielle Metallberufe Lernfelder 1 - 4*. Verlag Handwerk und Technik, 1. ed.

Haffer, Reiner; Becker-Kavan, Angelika; Einloft, Manred; Schulz, Elisabeth; Weihrauch, Bruno (2018): *Fachkenntnisse Zerspanungsmechaniker Lernfelder 5 - 12*. Verlag Handwerk und Technik, 3. ed.

Hajicek, Z. (2015): *SIMULATION OF VIRTUAL MACHINE TOOL DURING THE DEVELOPMENT PHASE*. Annals of DAAAM & Proceedings, 26:948–954.

Heeschen, Dominik; Klocke, Fritz; Arntz, Kristian (2015): *Life Cycle Oriented Milling Tool Management in Small Scale Production*. Procedia CIRP, 29:293–298.

Hehenberger, Peter (2011): *Computerunterstützte Fertigung - Eine kompakte Einführung*. Springer.

Hering, Ekbert; Schloske, Alexander (2019): *Fehlermöglichkeits- und Einflussanalyse - Methode zur vorbeugenden, systematischen Qualitätsplanung unter Risikogesichtspunkten*. Springer Vieweg, 1. ed.

Hofmann, Johann (2017): *Industrie 4.0 - Die digitale Fabrik - Auf dem Weg zur digitalen Produktion*. VDE Verlag, 1. ed.

Huang, Song; Yan, Guang (2011): *Research on Solution and Key Technologies of Network DNC for CNC Workshop*. Advanced Materials Research, 282-283:670–674.

IBM (2019): *Digital twin: Helping machines tell their story*. Available from: `https://www.ibm.com/internet-of-things/trending/digital-twin`. Last accessed on 05.02.2020.

IIM TU Darmstadt (2015a): *Arbeiten mit dem Postprozessor in NX*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/62_arbeiten_mit_dem_postprozessor_in_nx.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015b): *Das Maschinen-Koordinaten-System*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/47_das_maschinenkoordinatensystem.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015c): *Definition der Geometrie*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/48_definition_der_geometrie.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015d): *Erzeugung von Operationen*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/49_erzeugung_von_operationen.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015e): *Geometrie- und Werkzeugeinstellungen*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/4101_geometrie_und_werkzeugeinstellungen.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015f): *Maschinensteuerung*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/4104_maschinensteuerung.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015g): *Wegeinstellungen bei der Bearbeitung/Schnittmuster*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/4102_wegeinstellungen_bei_der_bearbeitungschnittmuster.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015h): *Zusammenbau der WKZ*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/723_zusammenbau_der_wkz.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015i): *Zusammenbau der WKZ - Basiskomponente hinzufügen*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/732_basiskomponente_einfgen.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015j): *Zusammenbau der WKZ - Einfügen der Komponenten*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/733_einfgen_der_komponenten.html`. Last accessed on 04.03.2020.

IIM TU Darmstadt (2015k): *Zusammenbau der WKZ - Einleitung*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/731_einleitung.html`.
Last accessed on 04.03.2020.

IIM TU Darmstadt (2015l): *Zusammenbau der WKZ - Maschine in NX-Bibliothek laden*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/741_maschine_in_nxbibliothek_laden.html`.
Last accessed on 04.03.2020.

IIM TU Darmstadt (2015m): *Zusammenbau der WKZ - Simulation*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/742_simulation.html`.
Last accessed on 04.03.2020.

IIM TU Darmstadt (2015n): *Zusammenbau der WKZ - Spindel und Arbeitsfläche definieren Spindel*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/734_spindel_und_arbeitsflche_definieren.html`.
Last accessed on 04.03.2020.

IIM TU Darmstadt (2015o): *Zusammenbau der WKZ - Werkzeugwechsler*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/736_werkzeugwechsler.html`.
Last accessed on 04.03.2020.

IIM TU Darmstadt (2015p): *Übung Post Builder*. Available from: `http://www.iim.maschinenbau.tu-darmstadt.de/kursunterlagen/cad_cam_2015/624_bung_post_builder.html`.
Last accessed on 04.03.2020.

Inellectsoft (2018): *Advanced Imaging Algorithms in Digital Twin Reconstruction of Construction Sites*. Available from: `https://www.intellectsoft.net/blog/advanced-imaging-algorithms-for-digital-twin-reconstruction/`.
Last accessed on 05.02.2020.

IT Production (2014): *Prozessunterstützung durch Identifikation*. Available from: `https://www.zoller.info/at/produkte/toolmanagement/datentransfer/rfid-chip`.
Last accessed on 27.03.2020.

Jedrzejewski, J.; Kwasny, W. (2015): *DEVELOPMENT OF MACHINE TOOL OPERATIONAL PROPERTIES*. Journal of Machine Engineering, 15:5–24.

Juschkat, Katharina (2018): *Intelligentes Rotorblatt reagiert auf Windstärken*. Available from:

`https://www.konstruktionspraxis.vogel.de/intelligentes-rotorblatt-reagiert-auf-windstaerken-a-694800/`.
Last accessed on 15.07.2020.

Kemptner, Peter (2016): *Integration in digitale Fabrik sichert Fertigungserfolg: CAM braucht Datendurchgängigkeit.* x-technik, pp. 62–64.

Kennedy, A; Ford, D (2003): *From manual grinding to CNC automation - a major step forward for the rod mill.* Transactions on Engineering Sciences, 44:579–588.

Kief, Hans; Roschiwal, Helmut; Schwarz, Karsten (2017): *CNC - Handbuch.* HANSER, 30. ed.

Kilic, Z.; Altintas, Yusuf (2016): *Generalized mechanics and dynamics of metal cutting operations for unified simulations.* International Journal of Machine Tools and Manufacture, 104:1–13.

Klocke, Fritz (2018): *Fertigungsverfahren 1 - Zerspanung mit geometrisch bestimmter Schneide.* Springer Vieweg, 9. ed.

Knapp, Gerald; Mukherjee, Tuhin; Zuback, James; Wei, Huiliang; Palmer, Todd; De, Amitava; Debroy, Tarasankar (2017): *Building blocks for a digital twin of additive manufacturing.* Acta Materialia, 135:390–399.

Knorr, Christine (2017): *FMEA – Fehlermöglichkeits- und Einflussanalyse.* Available from: `https://www.projektmagazin.de/methoden/fmea`.
Last accessed on 18.05.2020.

Kretzschmann, Ralf (2010): *Entwicklung eines automatisierten CNC-Prozessketten-Generators für spanende Werkzeugmaschinen.* SHAKER Verlag.

Kritzinger, Werner; Karner, Matthias; Traar, Georg; Henjes, Jan; Sihn, Wilfried (2018): *Digital Twin in manufacturing: A categorical literature review and classification.* IFAC-PapersOnLine, 51:1016–1022.

Lee, Jay; Lapira, Edzel; Bagheri, Behrad; Kao, Hung-An (2013): *Recent advances and trends in predictive manufacturing systems in big data environment.* Manufacturing Letters, 1:38–41.

Li, B.; Zhu, W.; Eynard, B.; Bricogne, M. (2014): *Researched on the Technology of Machining Simulation.* Advanced Materials Research, 1039:390–396.

Li, Chenzhao; Mahadevan, Sankaran; Ling, You; Wang, Liping; Choze, Sergio (2017): *A dynamic Bayesian network approach for digital twin.* 19th AIAA Non-Det. App. Conf.

Liu, Zheng; Meyendorf, Norbert; Mrad, Nezih (2018): *The role of data fusion in predictive maintenance using digital twin.* AIP Conference Proceedings, 1949:020–023.

Liukkonen, Mika (2014): *RFID technology in manufacturing and supply chain*. International Journal of Computer Integrated Manufacturing, 28:861–880.

Maier, W; Möhring, H; Werkle, K (2018): *Tools 4.0 – Intelligence starts on the cutting edge*. Procedia Manufacturing, 24:299–304.

Mansour Fallah, Solmaz; Trautner, Thomas; Pauker, Florian (2019): *Integrated tool lifecycle*. Procedia CIRP, 79:257–262.

Manufacturing Automation Laboratories (2017): *CUTPRO - Fundamentals of Machining*. Manufacturing Automation Laboratories Inc.

MARPOSS (2019): *Werkzeugkontrolle und Prüfung der Geometrien an Verarbeitungszentren*. Available from: `https://www.marposs.com/ger/application/tool-setting-and-geometric-checking-on-machining-center`. Last accessed on 17.06.2020.

MAV (2014): *Berührungslose Werkzeugkontrolle*. Available from: `https://mav.industrie.de/peripherie/beruehrungslose-werkzeugkontrolle/`. Last accessed on 17.06.2020.

Meseguer, A.; Gonzalez, F. (2008): *A methodology for cutting-tool management through the integration of CAPP and scheduling*. International Journal of Production Research, 46:1685–1706.

Microsoft (2017): *The promise of a digital twin strategy*. Available from: `https://info.microsoft.com/rs/157-GQE-382/images/Microsoft%27s%20Digital%20Twin%20%27How-To%27%20Whitepaper.pdf`. Last accessed on 05.02.2020.

Milekovic, Tihomir (2017): *Prozess FMEA*. Available from: `https://www.kvp.de/lexikon/prozess-fmea/#FMEA_Formblatt_P-FMEA`.

Last accessed on 18.05.2020.

Minautics (2019): *Prozess-FMEA Zusammenfassung*. Available from: `https://mi-nautics.com/prozess-fmea-anwendung-und-durchfuehrung/#4`. Last accessed on 18.05.2020.

Müller, Maximilian (2021): *Konzipierung einer Automatisierten Methode zur Generierung von Toolmanagement Stammdaten*. Technische Universität Graz - Institut für Fertigungstechnik.

NC matic (2017): *Spindle Speed Attached to a Tool*. Available from: `https://ncmatic.com/technical-tuesday/spindle-speed-value-for-tool/`. Last accessed on 23.07.2020.

Negri, Elisa; Fumagalli, Luca; Macchi, Marco (2017): *A Review of the Roles of Digital Twin in CPS-based Production Systems*. Procedia Manufacturing, 11:939–948.

Neugebauer, Reimund (2018): *Digitalisierung - Schlüsseltechnologien für Wirtschaft & Gesellschafft*. 1. ed.

NX Manufacturing (2019): *NX 9 Shop Docs Template Customization Tutorial*. Available from: `https://community.sw.siemens.com/s/article/nx-9-shop-docs-template-customization-tutorial`. Last accessed on 17.06.2020.

Oehler, Dominik (2016): *Definition der CAD/CAM/NC-Prozesskette auf Basis von Siemens NX10*. GRIN Verlag, 1. ed.

OEVE OENORM EN 60812 (2006): *Analysetechniken für die Funktionsfähigkeit von Systemen – Verfahren für die Fehlzustandsartund - auswirkungsanalyse (FMEA)*. Österreichisches Normungsinstitut.

Oracle (2017): *Digital Twins for IoT Applications*. Available from: `http://www.oracle.com/us/solutions/internetofthings/digital-twins-for-iot-apps-wp-3491953.pdf`. Last accessed on 05.02.2020.

Parrott, Aarom; Warshaw, Lana (2017): *Industry 4.0 and the digital twin - Manufacturing meets its match*. Available from: `https://www2.deloitte.com/us/en/insights/focus/industry-4-0/digital-twin-technology-smart-factory.html`. Last accessed on 05.02.2020.

Peng, Chong; Du, Hanheng; Liao, T. (2015): *A research on the cutting database system based on machining features and TOPSIS*. Robotics and Computer-Integrated Manufacturing, 43.

Pichler, Rudolf; Gerhold, Lukas (2020): *Seamless Data Integration in a CPPS with Highly Heterogeneous Facilities - Architectures and Use Cases Executed in a Learning Factory*. Springer International Publishing, pp. 1–10.

Porst, Rolf (2014): *Fragebogen - Ein Arbeitsbuch*. Springer, 4. ed.

Predix (2020): *Digital twin*. Available from: `https://www.ge.com/digital/applications/digital-twin`. Last accessed on 05.02.2020.

PROLIM (2012): *NX CAM: Customizing posts with Post Builder*. Available from: `https://www.prolim.com/nx-cam-customizing-posts-with-post-builder/`. Last accessed on 24.06.2020.

PTC (2019): *Digital twin: What Is Digital Twin Technology?* Available from:

`https://www.ptc.com/en/product-lifecycle-report/what-is-digital-twin-technology`.
Last accessed on 05.02.2020.

Rao, D; Patvardhan, C.; Singh, Ranjit (2011): *Intelligent Tool Management Strategies for Automated Manufacturing Systems*. Intelligent Control and Automation.

Raschinger, Marcus; Kipouridis, Orthodoxos; Gunthner, Willibald (2016): *A Service-Oriented Cloud Application for a Collaborative Tool Management System*. pp. 1–5.

Reifsnider, Kl; Majumdar, Prasun (2013): *Multiphysics Stimulated Simulation Digital Twin Methods for Fleet Management*. 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference.

Reinhart, Gunther (2017): *Handbuch Industrie 4.0 - Geschäftsmodelle, Prozesse, Technik*. HANSER.

Riedlsperger, Florian; Krenmayr, Bernhard; Zuderstorfer, Gerold; Fercher, Bernhard; Niederl, Bernd; Schmid, Johannes; Sonderegger, Bernhard (2020): *Application of an advanced mean-field dislocation creep model to P91 for calculation of creep curves and time-to-rupture diagrams*. 12:(100760).

Rockenschaub, Christoph (2021): *Erstellung eines Auswertealgorithmus zur Analyse und Komprimierung von ausgelesenen Maschinendaten*. Technische Universität Graz - Institut für Fertigungstechnik.

Rolls-Royce (2018): *Digital engine concept gets smart*. Available from:
`https://www.flightsafetyaustralia.com/2018/02/digital-engine-concept-gets-smart/`.
Last accessed on 28.02.2020.

Rolls-Royce (2019): *Pioneering the IntelligentEngine*. Available from:
`https://www.rolls-royce.com/products-and-services/civil-aerospace/intelligentengine.aspx`.
Last accessed on 28.02.2020.

Ríos, José; Hernandez-Matias, Juan; Oliva, Manuel; Mas, Fernando (2015): *Product Avatar as Digital Counterpart of a Physical Individual Product: Literature Review and Implications in an Aircraft*. Advances in Transdisciplinary Engineering, 2:657–666.

Sanchez Gomez, Carlos; Gil Castiblanco, Luis; Arroyo Osorio, José Manuel (2016): *Building a virtual machine tool in a standard PLM platform*. International Journal on Interactive Design and Manufacturing (IJIDeM), 11.

Schaupp, Eva; Abele, Eberhard; Metternich, Joachim (2016): *Evaluating Relevant Factors for Developing an Optimal Tool Storage Strategy*. Procedia CIRP, 55:23–28.

Schaupp, Eva; Abele, Eberhard; Metternich, Joachim (2017): *Potentials of Digitalization in Tool Management*. Procedia CIRP, 63:144–149.

Scheidegger, Patrick (2016): *CNC-CAM-Techniken - Die Vernetzung von Fertigungs und CNC-Techniken in der betrieblichen Praxis*. Dr.-Ing. Paul Christiani GmbH & Co. KG, 2. ed.

Schleich, Benjamin; Anwer, Nabil; Mathieu, Luc; Wartzack, Sandro (2017): *Shaping the digital twin for design and production engineering*. CIRP Annals - Manufacturing Technology, 66:141–144.

Schmid, Dietmar, Klein, Friedrich, Roller, Rolf, Behmel, Manfred, Heine, Burkhard, Schekulin, Karl; Dambacher, Michael; Kaufmann, Matthäus; Rhode, Gerd; Kaiser, Harald; Wahl, Roland; Berger, Uwe (2008): *Industrielle Fertigung - Fertigungsverfahren*. Europa Lehrmittel, 3. ed.

Schmid, Johannes (2018): *Modelling the microstructure of a creep resistant steel*. Technische Universität Graz - Institut für Werkstoffkunde, Fügetechnik und Umformtechnik.

Schmid, Johannes; Pichler, Rudolf (2020): *Seamless Data Integration in the CAM-NC Process Chain in a Learning Factory*. Procedia Manufacturing, 45:31–36.

Schmid, Johannes; Schmid, Alexander; Pichler, Rudolf; Haas, Franz (2020a): *Validation of machining operations by a Virtual Numerical Controller Kernel based simulation*. Procedia CIRP, 93:1478 – 1483.

Schmid, Johannes; Trabesinger, Stefan; Brillinger, Markus; Pichler, Rudolf; Wurzinger, Johannes; Ciumasu, Radu (2020b): *Tacit Knowledge Based Acquisition of Verified Machining Data*. pp. 117–121.

Schmid, Johannes; Vallant, Daniel; Butzerin, Andre; Brillinger, Markus; Suschnigg, Josef; Pichler, Rudolf; Haas, Franz (2021): *Acquisition of machine tool data via the open source implementation open62541 for OPC-UA*. Procedia CIRP. (Not published yet).

Schreiber, Werner; Zimmermann, Peter (2011): *Virtuelle Techniken im industriellen Umfeld: Das AVILUS-Projekt - Technologien und Anwendungen*. Springer.

Schroeder, Greyce; Steinmetz, Charles; Pereira, Carlos; Espíndola, Danúbia (2016): *Digital Twin Data Modeling with AutomationML and a Communication Methodology for Data Exchange*. IFAC-PapersOnLine, 49:12–17.

Siemens (2016): *Bibliothek für Bearbeitungsdaten*. Available from: `https://docs.plm.automation.siemens.com/tdoc/nx/10.0.3/nx_help/#uid:index_mfggeneral:xid384701:com_opts_edit_mach_data_lib`. Last accessed on 23.07.2020.

Siemens (2017a): *About ini files*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/`

`50552c77-74e4-45f8-aec1-baeb845bf6dc-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017b): *About Offsets*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/9a6e9f96-629e-4532-bbbb-22be69eabaa0-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017c): *Available Documentation*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/36e4bcef-1a0c-4aef-b88c-927f6ffa1f8d-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017d): *CSE Architecture Overview*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/0f290f27-306e-4b0d-ae70-2a1b96ca08d6-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017e): *CSE Concept and Naming*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/530a3bd9-da46-49ea-9c44-10516e81e33c-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017f): *Delivered with NX7.5*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/90b5cc78-19b8-4290-8609-d6105b2b82cc-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017g): *MTD vs CSE*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/8f8bee9a-d66f-4388-b2d6-9f44cb647520-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017h): *NX CAM ISV Architecture and Simulation Drivers*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/9101a1ff-eb31-4f8a-8551-e93b3815dd5f-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017i): *Simulation Overview - Levels of Simulation*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/98172385-9899-4d5d-8551-2520a108c5b4-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017j): *The 4 Main Modules of CSE*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/`

`13b872da-db84-4272-a102-5e7568bb54c5-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017k): *Things to Remember*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/f64f8759-b4fa-422e-b26d-b8c34d1e31d6-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2017l): *Toolchange Cycle - Anycontroller Language*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/f4263f8a-3717-4675-9297-2ab6a9f5843c-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018a): *5-axis transformation - Understanding the concept and handling of 5-axis transformation like TRAORI, G43.4 or M128*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/a56479eb-3712-4363-a7fd-c6484cd53f09-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018b): *Adding Doors to Toolchanger*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/184f513b-0b84-4c9b-a0ac-17e24012d3c1-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018c): *Changing the Kinematics Model*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/12851b7d-a94f-404a-a240-af0a97be3261-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018d): *Changing the Kinematics Model*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/e58da630-1034-4a36-84da-67389dd6cc7d-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018e): *Create a kinematics model*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/4538d844-8569-447c-b5d8-102d85ea064f-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018f): *Create a machine tool in the library*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/e2cc91fd-6803-4f93-a4f8-1d6c025d3b72-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2018g): *Creating documentation with Machine Configurator - Understanding the capability of Machine Configurator to create documentation*. Available from:

https://videos.mentor-cdn.com/mgc/videos/5400/416e3dfe-8811-4e34-b01b-2a5ff0a105d4-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018h): *Machine Configurator security concept - Understanding the capability of Machine Configurator protecting your data and how to use built-in security concepts*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/68bca8d0-9791-4d1a-821f-96c17dcdc3ab-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018i): *Motion planning and interpolation, accuracy of motions and time calculation - Understanding the details of motion planning. How kinematics information about acceleration and deceleration is covered. How accurate is the Simulation?* Available from: https://videos.mentor-cdn.com/mgc/videos/5400/be8a35cb-7f84-4322-9c48-203205fb81bd-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018j): *Non-linear transformations e.g. polar mode - Cover the non-linear transformation concept on the examples TRANSMIT/Polar mode*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/df14872f-7178-4f7d-9167-01ea7a2cf6fe-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018k): *Output messages - Understanding how to output messages and work with debug functions*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/06bea68e-dee3-45b2-8f28-08d0a4a854b5-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018l): *Overview Variable types - Understanding the concept of Variables*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/90df2240-ff2f-4817-8f5e-8dd2b35633ef-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018m): *Use and Test new Machine tool*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/724ca63d-eb84-4d4f-9723-531254cc3b71-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018n): *Using CCF-Files as libraries - Understanding the concept of MCF and CCF handling as libraries*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/65ac69b7-e8aa-4e2a-99f1-89986ee10719-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2018o): *Variables and Variable Methods - Understanding more about variables, special types of variable methods and variable listener*. Available from:

https://videos.mentor-cdn.com/mgc/videos/5400/75b331ac-659f-40dc-a8df-22a44118adc0-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019a): *Axis and Channel configuration for Siemens 840D - Understanding axis and channel configurations*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/28a8c645-8e30-47b9-9ba6-591fdaa12b60-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019b): *Create MCF from scratch - Your first steps creating an MCF file from scratch*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/ab7c2692-ff1b-4f48-b515-822b51d66c5b-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019c): *Digital twin*. Available from: https://www.plm.automation.siemens.com/global/de/our-story/glossary/digital-twin/24465. Last accessed on 05.02.2020.

Siemens (2019d): *Feedrate move G1 X F - Add and create meta codes for cutting feed rate movements like G1 X F*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/00eb0f66-e81c-45a2-8d5f-3a4e199b083a-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019e): *First NC-Codes rapid move G0 X - Add and create meta codes for rapid motions like G0*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/491cc0b9-c2be-4f2e-aa18-e88ffa48611c-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019f): *Incremental mode - Understanding global and incremental modes*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/0e6ba9d8-1c48-46c6-9797-d92d643554bd-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019g): *Load Offset to use Geometry view MCS - Understanding offsets in conjunction with the geometry view of the ONT in NX CAM. Using the LoadOffset function*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/434c1733-f611-4f2a-8b3a-6b0ebca4512b-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019h): *Local Offsets ROT, AROT - Learn more about transformations and local offsets like ROT and AROT*. Available from: https://videos.mentor-cdn.com/mgc/videos/5400/cba64af3-0882-44e9-8bc3-68d37a6b8af2-en-US-video.mp4. Last accessed on 07.02.2020.

Siemens (2019i): *Local offsets TRANS, ATRANS - Learn more about transformations and local offsets like TRAN or ATRANS*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/7e75c7f8-3ccc-4de1-8ada-68c67b8c83cf-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019j): *Overview Siemens FRAME concept - Understanding the transformation concept of Sinumerik FRAME objects*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/601230e7-3157-414a-b43d-f29038cb537a-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019k): *Reusing things using methods - Understanding the method concept and its benefits*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/c5ca12cc-6425-4fde-a90c-89856fd0b28c-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019l): *Spindle modes - Understand how different spindle modes and speeds are handled*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/87a14f12-2193-48fc-8249-4a12151fb7aa-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019m): *Subprogram handling - Understanding how subprograms are handled within CSE*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/0e9248cd-83a7-4600-824d-7fbdd518b29d-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019n): *Tool length compensation - Understanding the concept of the tool length compensation*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/436ded2c-9c92-4013-b430-8fb87449cf98-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019o): *Tool radius compensation - Understanding the concept of the tool radius compensation*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/d636a129-414e-4a05-9df5-ea29f8e33a43-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019p): *Toolchange T M6 - different controllers - Understanding the tool change concepts for different controller types like Sinumerik, Fanuc or TNC*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/787b9f4f-64d4-4ae2-93a5-edbc4803fab9-en-US-video.mp4`. Last accessed on 07.02.2020.

Siemens (2019q): *Toolchange T M6 - Understanding tool changes in detail*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/`

`2408bb20-ab47-49c7-a7d1-e36cd31134d5-en-US-video.mp4`.
Last accessed on 07.02.2020.

Siemens (2019r): *Zero offset G53 - Understanding the concept of zero offsets*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/271de032-450d-489d-a24f-be342fb89993-en-US-video.mp4`.
Last accessed on 07.02.2020.

Siemens (2019s): *Zero offset G54 - first version - Understanding the concept and handling of offsets like G54. This is the overview section, details in the following sections*. Available from: `https://videos.mentor-cdn.com/mgc/videos/5400/f0732384-307b-474a-a1b7-5df3cd245a35-en-US-video.mp4`.
Last accessed on 07.02.2020.

Siemens AG (2017): *SINUMERIK 840D sl Fundamentals*. Siemens.

Siemens AG (2018a): *SINUMERIK 840D sl CNC Commissioning: NC, PLC, Drive*. Siemens.

Siemens AG (2018b): *SinuTrain - der steuerungsidentische NC-Programmierplatz*. Siemens.

Siemens AG (2019a): *CNC4you - Praxiswissen für die Fertigung*. Siemens.

Siemens AG (2019b): *SINUMERIK - Intelligente Lösungen für Werkzeugmaschinen*. SINUMERIK.

Siemens Digital Industries Software (2020): *Teamcenter*. Available from: `https://www.plm.automation.siemens.com/global/de/products/teamcenter/`.
Last accessed on 24.03.2020.

Siemens Industry Online Support (2010): *SINUMERIK 840D sl / 828D Arbeitsvorbereitung*. Available from: `https://support.industry.siemens.com/cs/mdm/25034189?c=19609929099&lc=de-AT`.
Last accessed on 10.08.2020.

Siemens PLM Software (2009): *Postbuilder Release Notes 7.5*. Siemens PLM Software.

Siemens PLM Software (2015): *NX Tooling*. Available from: `https://www.geoplm.com/knowledge-base-resources/NX2018/manufacturing/Brochures/4672_tcm1023-4494.pdf`.
Last accessed on 23.07.2020.

Siemens PLM Software (2018): *Defining closed-loop manufacturing - Using manufacturing operations management to power smart manufacturing*. Siemens.

SIM-CI (2018): *Digital twin cities*. Available from: `https://www.sim-ci.com`.
Last accessed on 05.02.2020.

SPINNER Werkzeugmaschinenfabrik GmbH (2019): *SPIOS Dokumentation.* SPINNER Werkzeugmaschinenfabrik GmbH.

Stackpole, Beth (2015): *Digital Twins Land a Role In Product Design.* Available from: `https://www.digitalengineering247.com/article/digital-twins-land-a-role-in-product-design/`. Last accessed on 05.02.2020.

Stark, Rainer; Kind, Simon; Neumeyer, Sebastian (2017): *Innovations in digital modelling for next generation manufacturing system design.* CIRP Annals - Manufacturing Technology, 66:169–172.

Stoldt, Johannes; Trapp, Thies; Toussaint, Stefan; Süße, Marian; Schlegel, Andreas; Putz, Matthias (2018): *Planning for Digitalisation in SMEs using Tools of the Digital Factory.* Procedia CIRP, 72.

Storm, Martin (1993): *Werkstattinformationssysteme.* Springer-Verlag Berlin Heidelberg, 1. ed.

Swedberg, Claire (2018): *Digital Twins Bring Value to Big RFID and IoT Data.* Available from: `https://www.rfidjournal.com/articles/view?17421/2`. Last accessed on 05.02.2020.

Systema Engineering (2020): *Prozess-FMEA.* Available from: `http://www.systema-gmbh.de/methoden/fmea/prozess-fmea/`. Last accessed on 18.05.2020.

Söderberg, Rikard; Wärmefjord, Kristina; Carlson, Johan; Lindkvist, Lars (2017): *Toward a Digital Twin for real-time geometry assurance in individualized production.* CIRP Annals - Manufacturing Technology, 66:137–140.

Tao, Fei; Cheng, Jiangfeng; Qi, Qinglin; Zhang, Meng; Zhang, He; Sui, Fangyuan (2018): *Digital twin-driven product design, manufacturing and service with big data.* The International Journal of Advanced Manufacturing Technology, 94:3563–3576.

Tao, Fei; Cheng, Ying; Cheng, Jiangfeng; Zhang, Meng; Xu, Wenjun; Qi, Qinglin (2017): *Theory and technologies for cyber-physical fusion in digital twin shop-floor.* Computer Integrated Manufacturing Systems, 23:1603–1611.

Tao, Fei; Zahng, Meng; Nee, AYC (2019): *Digital Twin Driven Smart Manufacturing.* ACADEMIC PRESS, 1. ed.

TCM International (2021): *TOOLTRACER - Werkzeugstammdaten endlich fehlerlos verfügbar machen.* Available from: `http://www.tooltracer.com`. Last accessed on 14.04.2021.

Teti, R.; D'Addona, Doriana (2011): *TRIZ based tool management in supply networks.* Procedia Engineering, 9:680–687.

Trabesinger, Stefan; Butzerin, Andre; Schall, Daniel; Pichler, Rudolf (2020): *Analysis of High Frequency Data of a Machine Tool via Edge Computing.* Procedia Manufacturing, 45:343–348.

Tseng, Ginette; Chen, Christina; Erkorkmaz, Kaan; Engin, Serafettin (2019): *Digital shadow identification from feed drive structures for virtual process planning.* CIRP Journal of Manufacturing Science and Technology, 24:55–65.

Tuegel, Eric (2012): *The Airframe Digital Twin: Some Challenges to Realization.* Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference.

Tönnes, Christian; Schuh, Günther; Dölle, Christian (2018): *Methodology for the derivation of a digital shadow for engineering management.* 2018 IEEE Technology and Engineering Management Conference (TEMSCON).

Vachálek, Ján; Bartalsky, Lukas; Rovný, Oliver; Sismisova, Dana; Morhac, Martin; Loksik, Milan (2017): *The digital twin of an industrial production line within the industry 4.0 concept.* 21st International Conference on Process Control, pp. 258–262.

Vajna, Sandor; Weber, Christian; Schlingensiepen, Jürgen; Schlottmann, Dietrich (1994): *CAD/CAM für Ingenieure - Hardware - Software - Strategien.*

Vallant, Daniel (2020): *Acquisition and processing of machine data on a machining center in view of data traceability and open-source implementations of OPC UA in cooperation with smartfactory@tugraz.* FH JOANNEUM - University of Applied Sciences.

VDI 3321 (1994): *Schnittwertoptimierung Grundlagen und Anwendung.* Verein Deutscher Ingenieure.

VDI 4499 (2008): *Digitale Fabrik Grundlagen, Digital factory Fundamentals.* Verein Deutscher Ingenieure.

Vogel-Heuser, Birgit; Bauernhansl, Thomas; Hompel, Michael (2017a): *Handbuch Industrie 4.0 Bd.1: Produktion.*

Vogel-Heuser, Birgit; Bauernhansl, Thomas; Hompel, Michael (2017b): *Handbuch Industrie 4.0 Bd.2: Automatisierung.*

Walsh, Kevin (2019): *A new take on the digital twin.* Available from: `https://www.bsquare.com/`. Last accessed on 05.02.2020.

Wang, Qi; Gu, Ya; An, Dong (2012): *Research and Development of Complex Curved Surface*

Mechanism Parts Based on Network CAD/CAM/DNC. Applied Mechanics and Materials, 241-244:2149–2152.

Waurzyniak, Patrick (2016): *New Machine Analytics Software Offers Digital Twin Modeling of the Factory Floor*. Available from:
`https://bit.ly/397Joyk`.
Last accessed on 05.02.2020.

Waycott, Andrew (2017): *What is a Digital Twin?* Available from:
`https://www.twinthread.com/2017/05/11/what-is-a-digital-twin/`.
Last accessed on 05.02.2020.

Weber, Christian; Königsberger, Jan; Kassner, Laura; Mitschang, Bernhard (2017): *M2DDM – A Maturity Model for Data-Driven Manufacturing*. Procedia CIRP, 63:173–178.

Werdich, Martin (2012): *FMEA – Einführung und Moderation - Durch systematische Entwicklung zur übersichtlichen Risikominimierung*. Springer Vieweg, 2. ed.

Westkämper, Engelbert; Löffler, Carina (2016): *Strategien der Produktion - Technologien, Konzepte und Wege in die Praxis*. Springer Vieweg.

Wohlfeld, Denis; Weiss, V.; Becker, B. (2017): *Digital Shadow – From production to product*, pp. 783–794.

Woo, Y.; Wang, Eric; Kim, Yong; Rho, H.M. (2005): *A Hybrid Feature Recognizer for Machining Process Planning Systems*. CIRP Annals - Manufacturing Technology, 54:397–400.

Xiang, Sitong; Shen, Mu; Yang, Jian (2013): *Distributed Numerical Control Strategy for Error Compensation on CNC Machine Tools*. Applied Mechanics and Materials, 415:188–191.

Xu, Xun; Nee, Andrew (2009): *Advanced Design and Manufacturing Based on STEP*. 1. ed.

Xun, Jingbin; Wang, Gang; Qiao, Zhifeng; Ding, Yanyu; Ling, Xianggui; Tang, Zhiyuan (2012): *The Development of DNC Transfer Software Used In CNC Machine Tools*. Applied Mechanics and Materials, 141:550–553.

Zainzinger, D; Heiss, M (2020): *Optimierungspotential durch Closed Loop Manufacturing*. Elektrotechnik und Informationstechnik.

Zhang, En; Wang, Li (2016): *Relevant Applications of Tools in UG NX CAM Module*. MATEC Web of Conferences, 63:1–4.

Zhang, Hao; Liu, Qiang; Chen, Xin; Zhang, Ding; Leng, Jiewu (2017): *A Digital Twin-Based Approach for Designing and Multi-Objective Optimization of Hollow Glass Production Line*. IEEE Access, 5:26901–26911.

Zhuang, Cunbo; Liu, Jianhua; Xiong, Hui (2018): *Digital twin-based smart production management and control framework for the complex product assembly shop-floor.* The International Journal of Advanced Manufacturing Technology, 96:1149–1163.

Zoller (2016): *ZOLLER-Werkzeug-Messprogramm - Lasso - zur Konturverlaufsmessung.* Available from: `https://bit.ly/3fXoWqE`.
Last accessed on 23.07.2020.

Zoller (2018a): *DNC Ausgabeformate.* Available from:
`https://www.zoller.info/at/footer/produkte/ausgabeformate`.
Last accessed on 23.07.2020.

Zoller (2018b): *RFID-Technologie.* Available from: `https://www.zoller.info/at/produkte/toolmanagement/datentransfer/rfid-chip`.
Last accessed on 27.03.2020.

Zoller (2018c): *zidCode.* Available from: `https://www.zoller.info/de/produkte/toolmanagement/datentransfer/zidcode`.
Last accessed on 27.03.2020.

A. Appendix

A.1. Different Definitions of the Term Digital Twin

Tables 24 and 25 show the most relevant examples of DT's various definitions, listed according to the views of universities and enterprises.

Table 24.: Theoretical concept of Digital Twin
Source: Tao et al. (2019), pp.8-10 (extended with further definitions).

Research field	**Universities / Institutes**	**Theoretical concept**
Prognostics and Health Management	U.S. Air Force Research Laboratory University of California University of Illinois	*"An ultra-realistic model of an as-built and maintained aircraft that is explicitly tied to the materials and manufacturing specifications, controls, and processes used to build and maintain a specific airframe"* [1,2]
	University of South Carolina	*"Integrating ultra-high fidelity simulation with on-board health management system, maintenance history, and historical vehicle and fleet data to mirror the life of a specific flying physical twin to enable significant gains in safety and reliability"* [3]
	University of Cincinnati	*"A digital model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms as well as other available physical knowledge"* [4]

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[1] cf. Tuegel, (2012).
[2] cf. Gockel et al., (2012).
[3] cf. Reifsnider / Majumdar, (2013).
[4] cf. Lee et al., (2013).

	Belarusian State University of Informatics and Radioelectronics	*"A digital replica of real physical of real physical installation, which can check the consistency for monitoring data, perform data mining to detect existing and forecast upcoming problems, and use AI knowledge engine to support effective business decisions"* [5]
	Vanderbilt University GE Global Research Center	*"A digital model that flies virtually through the same load history as the actual aircraft wing, integrates various uncertainty sources over the entire life of aircraft wing and heterogeneous information, reduces the uncertainty in model parameters, tracks the time- dependent system states using measurement data, and predicts the evolution of damage states if no data is available"* [6]
	University of British Columbia Iowa State University Department of National Defense Canada	*"A living model that continually adapts to changes in the environment or operation using in the environment or operation using real-time sensory data and can forecast the future of the corresponding physical assets for predictive maintenance"* [7]
Production	University of Stuttgart	*"A digital representation that contains all the states and functions of a physical asset and has the possibility to collaborate with other digital twins to achieve a holistic intelligence that allows for decentralized selfcontrol"* [8]
	Politecnico di Milano	*"A virtual and computerized counterpart of a physical system that can exploit a real-time synchronization of the sensed data coming from the field and is deeply linked with Industry 4.0"* [9]

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[5] cf. Asimov et al., (2018).

[6] cf. Li et al., (2017).

[7] cf. Liu et al., (2018).

[8] cf. Weber et al., (2017).

[9] cf. Negri et al., (2017).

	Chalmers University of Technology Fraunhofer-Chalmers Centre for Industrial Mathematics	*"A digital copy of a product or a production system, going across the design, preproduction, and production phases and performing real-time optimization"* [10]
	Reutlingen University	*"A digital copy of a real factory, machine, worker etc., which is created and can be independently expanded, automatically updated as well as being globally available in real-time"* [11]
	Beijing Institute of Technology	*"A dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behavior, life, and performance in a timely fashion"* [12]
	University of Applied Science of Southern Switzerland	*"A digital avatar encompassing CPS data and intelligence, representing structure, semantics, and behavior of the associated CPS, and providing services to mesh the virtual and physical worlds"* [13]
	The Pennsylvania State University Indiana Institute of Technology	*"A rigorous validation for additive manufacturing process, predicting the most important variables that affect the metallurgical structure and properties of the components, and replacing expensive, time-consuming physical experiments with rapid, inexpensive numerical experiments"* [14]
PLM	Polytechnic University of Madrid and AIRBUS Group	*"A product equivalent digital counterpart that exists along the product lifecycle from conception and design to usage and serving, knows the product past, current and possible future states, and facilitates the development of product related intelligent services"* [15]

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[10] cf. Söderberg et al., (2017).

[11] cf. Brenner / Hummel, (2017).

[12] cf. Zhuang et al., (2018).

[13] cf. Ciavotta et al., (2017).

[14] cf. Knapp et al., (2017).

[15] cf. Ríos et al., (2015).

	Friedrich-Alexander-Universität Erlangen-Nürnberg University Paris-Sud	*"A bidirectional relation between a physical artifact and the set of its virtual models, enabling the efficient execution of product design, manufacturing, servicing, and various other activities throughout the product lifecycle"* [16]
	Ruhr University of Bochum	*"Having a high semantic content and considering both virtual product models as well as feedback data from the physical product along its whole lifecycle"* [17]
	Federal University of Rio Grande do Sul	*"A set of models from different stages of product lifecycle, such as the system models, functional models, 3D geometric models, and usage models, which are kept interacting with each other"* [18]
Design	Technische Universität Berlin Fraunhofer Institute Production Systems and Design	*"Consisting of a unique instance of the universal digital master model of an asset, its individual digital shadow, and an intelligent linkage (algorithm, simulation model, correlation, etc.) of the two elements above"* [19]
	Guangong University of Technology	*"Realistic product and production process models linking enormous amounts of data to fast simulation and allowing the early and efficient assessment of the consequences, performance, quality of the decisions on products and production line"* [20]
	University of Ottawa	*"The cyber layer of CPS, which evolves independently and keeps close integration with the physical layer"* [21]

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[16] cf. Schleich et al., (2017).
[17] cf. Abramovici et al., (2016).
[18] cf. Schroeder et al., (2016).
[19] cf. Stark et al., (2017).
[20] cf. Zhang et al., (2017).
[21] cf. Alam / El Saddik, (2017).

Table 25.: Digital Twin in the eyes of enterprises
Source: Tao et al. (2019), pp.12-14 (extended with further definitions).

Company	**Industrial concept**	**Related products/ tools**
Siemens	"*Including product digital twins for efficient design of new products, production digital twins for manufacturing and production planning, and performance digital twins for capturing, analyzing, and acting on operational data*" [22]	Siemens PLM Software
General Electric Company (GE)	*"Providing a software representation of a physical asset based on Predix Platform and enabling companies to better understand, predict, and optimize the performance of each unique asset"* [23]	Predix platform
Parametric Technology Corporation (PTC)	*"A digital representation of a specific asset in the field, including current and past configuration states, taking into account serialized parts, software versions, options, and variants"* [24]	PTC Creo
Dassault	*"A virtual equivalent to a physical product, which can improve manufacturing excellence by allowing people across the enterprise to better collaborate and achieve continuous process improvement"* [25]	3D experience platform
Oracle	*"An important concept that is going to be strategic to business operations as IoT deployments proliferate through organization"* [26]	Oracle IoT cloud
ANSYS	*"Combining all the organization's digital information on a specific product and merging physics-based understanding with analytics"* [27]	CAE tools
International Business Machines Corporation (IBM)	*"A virtual representation of a physical object or system across its lifecycle, using a real-time data to enable understanding learning, and reasoning"* [28]	IBM Watson IoT platform

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[22] cf. Siemens, (2019c), Online-source [05.02.2020].
[23] cf. Predix, (2020), Online-source [05.02.2020].
[24] cf. PTC, (2019), Online-source [05.02.2020].
[25] cf. Grieves, (2015), Online-source [05.02.2020].
[26] cf. Oracle, (2017), Online-source [05.02.2020].
[27] cf. ANSYS, (2017), Online-source [05.02.2020].
[28] cf. IBM, (2019), Online-source [05.02.2020].

System Applications and Products (SAP)	*"A live digital representation (or software model) of a connected physical object"* [29]	SAP Leonardo platform
Altair	*"A capability with which product performance is predicted, optimized, tracked, and measured throughout the product lifecycle"* [30]	CAE tools
Microsoft	*"Visualizing the physical world, being intelligent, collaborative, interactive and immersive, and providing a method to simulate electronic, mechanical, and combined system outcomes"* [31]	Azure IoT Hub Microsoft HoloLens
TIBCO Software	*"A software representation of a device that can create efficiencies across the entire product lifecycle"* [32]	Project Flogo and TIBCO Graph Database
TwinThread	*"A digital representation of any physical asset, including all information about the asset current and historical running conditions"* [33]	Software solution
Bsquare	*"Digital representations of real-time configuration and state information for physical devices"* [34]	Bsquare IoT
Sight Machine	*"Offering sets of analytical models that mirror the entire production process, encompassing machines, lines, plants, or supply chains"* [35]	Sight Machine Platform
Simulating Critical Infrastructures (SIM-CI)	*"A digital copy of a city allowing us to accurately mimic its vital infrastructures"* [36]	DT cities platform
Det Norske Veritas and Germanischer Lloyd (DNV GL)	*"A digital, virtual representation of an asset, maintained throughout the lifecycle and easily accessible at any time"* [37]	DNV GL - Software

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[29] cf. Ammermann, (2017), Online-source [05.02.2020].
[30] cf. Altair, (2019), Online-source [05.02.2020].
[31] cf. Microsoft, (2017), Online-source [05.02.2020].
[32] cf. Canton, (2017), Online-source [05.02.2020].
[33] cf. Waycott, (2017), Online-source [05.02.2020].
[34] cf. Walsh, (2019), Online-source [05.02.2020].
[35] cf. Waurzyniak, (2016), Online-source [05.02.2020].
[36] cf. SIM-CI, (2018), Online-source [05.02.2020].
[37] cf. DNV-GL, (2018), Online-source [05.02.2020].

PACCAR	*"A virtual version of an engine based on sensor data from the real-word versions to manage the maintenance and repair of engines"* [38]	DataV system
Deloitte	*"An evolving digital profile of the historical and current behavior of a physical object or process that helps optimize business performance"* [39]	IoT solution
Intellectsoft	*"A real-time digital representation of a physical object that continuously monitors changes in environment and reports back the update state in the form of measurements and pictures"* [40]	AR solution
Infosys	*"Virtual replications of physical products, systems, and processes that are indistinguishable from their real counterparts"* [41]	Infosys NiaTM platform
Autodesk	*"Spanning both the factory and product, and making use of augmented reality technologies borrowed from media and entertainment software line as well as capabilities from SeeControl, an IoT cloud services platform provider"* [42]	Reality technology and design software

A.1.1. Different Subdivisions of a Digital Twin According to Grieves and Vickers

*"**Digital Twin Prototype (DTP)** — this type of Digital Twin describes the prototypical physical artifact. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version. These informational sets include, but are not limited to, Requirements, Fully annotated 3D model, Bill of Materials (with material specifications), Bill of Processes, Bill of Services, and Bill of Disposal."* [43]

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[38] cf. Swedberg, (2018), Online-source [05.02.2020].

[39] cf. Parrott / Warshaw, (2017), Online-source [05.02.2020].

[40] cf. Inellectsoft, (2018), Online-source [05.02.2020].

[41] cf. Aggarwal / Varghese, (2017), Online-source [05.02.2020].

[42] cf. Stackpole, (2015), Online-source [05.02.2020].

[43] cf. Grieves / Vickers, (2017), p.94.

*"**Digital Twin Instance (DTI)** — this type of Digital Twin describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product. Depending on the use cases required for it, this type of Digital Twin may contain, but again is not limited to, the following information sets: A fully annotated 3D model with Geometric Dimensioning and Tolerancing (GD&T) that describes the geometry of the physical instance and its components, a Bill of Materials that lists current components and all past components, a Bill of Process that lists the operations that were performed in creating this physical instance, along with the results of any measurements and tests on the instance, a Service Record that describes past services performed and components replaced, and Operational States captured from actual sensor data, current, past actual, and future predicted."* [44]

*"**Digital Twin Environment (DTE)** — this is an integrated, multi-domain physics application space for operating on Digital Twins for a variety of purposes."* [45]

These purposes would include:

*"**Predictive** — the Digital Twin would be used for predicting future behavior and performance of the physical product. At the Prototype stage, the prediction would be of the behavior of the designed product with components that vary between its high and low tolerances in order to ascertain that the as-designed product met the proposed requirements. In the Instance stage, the prediction would be a specific instance of a specific physical product that incorporated actual components and component history. The predictive performance would be based from current point in the product's lifecycle at its current state and move forward. Multiple instances of the product could be aggregated to provide a range of possible future states."* [46]
*"**Interrogative** — this would apply to DTI's. Digital Twin Instances could be interrogated for the current and past histories. Irrespective of where their physical counterpart resided in the world, individual instances could be interrogated for their current system state: fuel amount, throttle settings, geographical location, structure stress, or any other characteristic that was instrumented. Multiple instances of products would provide data that would be correlated for predicting future states. For example, correlating component sensor readings with subsequent failures of that component would result in an alert of possible component failure being generated when that sensor pattern was reported. The aggregate of actual failures could provide Bayesian probabilities for predictive uses."* [47]

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[44] cf. Grieves / Vickers, (2017), p.94.
[45] cf. Grieves / Vickers, (2017), p.94.
[46] cf. Grieves / Vickers, (2017), pp.94-95.
[47] cf. Grieves / Vickers, (2017), pp.94-95.

A.1.2. Different Subdivisions of a Digital Twin According to Siemens

*"**Product Digital Twins** — Digital twins can be used to virtually validate product performance, while also showing how your products are currently acting in the physical world. This "product digital twin" provides a virtual-physical connection that lets you analyze how a product performs under various conditions and make adjustments in the virtual world to ensure that the next physical product will perform exactly as planned in the field. It doesn't matter if you have complex systems and materials – product digital twins help you navigate that complexity to make the best possible decisions. All of this eliminates the need for multiple prototypes, reduces total development time, improves quality of the final manufactured product, and enables faster iterations in response to customer feedback."* [48]

*"**Production Digital Twins** — A production digital twin can help validate how well a manufacturing process will work on the shop floor before anything actually goes into production. By simulating the process using a digital twin and analyzing why things are happening using the digital thread, companies can create a production methodology that stays efficient under a variety of conditions. The production can be optimized even further by creating product digital twins of all the manufacturing equipment. Using the data from the product and production digital twins, businesses can prevent costly downtime to equipment – and even predict when preventative maintenance will be necessary. This constant stream of accurate information enables manufacturing operations that are faster, more efficient, and more reliable."* [49]

*"**Performance Digital Twins** — Smart products and smart plants generate massive amounts of data regarding their utilization and effectiveness. The performance digital twin captures this data from products and plants in operation and analyzes it to provide actionable insight for informed decision making"* [50]

A.2. Risk Analysis

The entire Risk Analysis is depicted within the following Tables 26 to 33.

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[48] cf. Siemens, (2019c), Online-source [23.02.2020].

[49] cf. Siemens, (2019c), Online-source [23.02.2020].

[50] cf. Siemens, (2019c), Online-source [23.02.2020].

A.2.1. PLM Software

Table 26.: PFMEA - Risk Analysis of the PLM Software
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Function: Providing CAM templates										
1	Appropriate machine tool, PP, tools or clamping devices not provided	Manual selection of tools and clamping devices	2	Incomplete Template	Release after test run	2	Visual inspection	1	4	4
2	CAM template for wrong machine tool loaded	Reload of the template required	1	Wrong template selected	Input mask with instructions	2	Visual inspection	2	2	4
Function: Saving and linking of the data										
3	Incorrect naming of the data	Data cannot be found easily	2	Wrong name assigned	Input mask with instructions	1	Using impact analysis	1	2	2
4	Incorrect classification of the data	Data not found easily	2	Wrong classification selected	Input mask with instructions	1	Using impact analysis	1	2	2
Function: Release of the data										
5	Incomplete or wrong data released	Possible collision on the real machine tool	10	Data was mixed up	Work instruction	1	four-eyes release process	1	10	10

Function: Transfer of manufacturing data										
6	Data not transferred	Production cannot start	6	No transfer destination stored	Work instruction	2	four-eyes release process	2	12	24
7	Data sent to the wrong machine	Production cannot start	6	Wrong transfer destination stored	Work instruction	2	four-eyes release process	2	12	24

A.2.2. Tool Management Software

Table 27.: PFMEA - Risk Analysis of the Tool Management Software
Source: Own illustration.

Nr.	**Potential failure**	**Potential effect(s) of failure**	**S**	**Potential cause(s) of failure**	**Current preventive action**	**O**	**Detective action**	**D**	**SxO**	**RPN**
Function: Generation of tool components										
8	Wrong geometry created	Possible collision on the real machine tool	10	Data mixed up	Input mask with instructions	3	CAM simulation or presetting machine	2	30	60
9	Wrong material assigned	Wrong values from MDL	7	Data was mixed up	Input mask with instructions	1	Visual inspection	1	7	7
10	Wrong coordinate systems assigned	Digital assembly process not possible	1	Typing error	Input mask with instructions	3	Visual inspection	1	3	3

11	Wrong connection codes assigned	Digital assembly process not possible	1	Typing error	Input mask with instructions	2	Visual inspection	1	2	2
12	Wrong classification	Digital assembly process not possible	1	Typing error	Input mask with instructions	1	Visual inspection	1	1	1
Function: Generation of complete tools										
13	Tooltip incorrectly defined	CAM Simulation is carried out incorrectly	2	Typing error	Work instruction	1	CAM simulation	1	2	2
14	Wrong coordinate system of the holder	Digital tool incorrectly installed	3	Typing error	Work instruction	1	CAM simulation	1	3	3
15	Wrong classification of the complete tool	Digital tool not found easily	2	Typing error	Work instruction	1	CAM simulation	1	2	2
16	Wrong definition of CUT, NOCUT and holder	CAM Simulation cannot be carried out	2	Typing error	Work instruction	1	CAM simulation	1	2	2
17	Wrong definition of CUTCOM or ADJUST register	Possible collision on the real machine tool	10	Typing error	Work instruction	1	CAM simulation	1	10	10
Function: Generation of tool component lists										
18	Components not assigned	Tool component list cannot be generated	3	Components are not defined in the TMS	Input mask with instructions	2	Search Function	2	6	12
19	Location of components not determined	Tool component list cannot be generated	3	Component location not defined	Input mask with instructions	2	Search Function	2	6	12

Function: Generation of tool set-up lists										
20	Wrong set-up instruction generated	Complete tool assembled incorrectly	5	Typing error	Work instruction	3	Presetting machine	1	15	15
Function: Generation of measuring instructions										
21	Wrong measuring instruction generated	Measuring process must carried out manually	3	Typing error	Work instruction	1	Presetting machine	2	3	6

A.2.3. MDL Software

Table 28.: PFMEA - Risk Analysis of the MDL Software
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Function: Saving of machining data										
22	Insufficient combinations entered	CAM operator influenced by wrong values	5	Typing error	Work instruction	4	Visual inspection	6	20	120
Function: Providing of machining data										
23	Interpolation of the data caused errors	CAM operator influenced by wrong values	5	Too few values in the database	Work instruction	7	Visual inspection	6	35	210

A.2.4. CAM Software

Table 29.: PFMEA - Risk Analysis of the CAM Software
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Function: Import of the tool data										
24	Import impossible	Tools cannot be loaded	2	Required network drive not connected	Work instruction	1	Visual inspection	2	2	4
Function: Digital set-up process of the machine tool										
25	Raw material or workpiece not defined	CAM simulation is not possible	2	Typing error	Work instruction	2	Visual inspection	1	4	4
26	Inadequate digital clamping device / situation selected	Real machining is carried out with a non-simulated clamping situation	5	Rework of the CAM process was waived	Work instruction	2	Visual inspection	2	10	20
		Rework of the CAM program	2	Real clamping situation deviates too much from the digital one	Work instruction	2	Visual inspection	2	4	8
Function: Planning of the manufacturing process										
27	Inappropriate machining operations selected	Rework of the CAM process	2	Typing error	Templates	2	CAM simulation and analysis methods	2	4	8

28	Wrong tools selected	Rework of the CAM process	2	Typing error	Templates	1	CAM simulation and analysis methods	1	2	2
29	Inappropriate machining data selected	Quality of the real workpiece is insufficient	7	Human error	MDL	3	Visual inspection	6	21	126
		Possible collision on the real machine tool	10	Human error	MDL	3	Visual inspection	6	30	180
30	Manufacturing of the workpiece not completely planned	Real workpiece not completely manufactured	5	Wrong analyzing method selected	Work instruction	2	Visual inspection	2	10	20

Function: Analysis of the manufacturing process

31	Wrong analyzing method selected	Manufacturing of the workpiece not completely planned	4	Typing error	Work instruction	2	Visual inspection	1	8	8

Function: Generation of the NC code

32	Generation of the NC code without CAM simulation	Possible collision on the real machine tool	10	Typing error	Work instruction	1	Visual inspection	1	10	10
33	Wrong PP selected	Possible collision on the real machine tool	10	Typing error	Work instruction	1	Visual inspection	1	10	10
		NC code cannot be executed on the machine tool	6	Typing error	Work instruction	1	Visual inspection	1	6	6

Function: Generation of the Shop Documentation										
34	Wrong documentation generated	Possible collision on the real machine tool	10	Wrong template selected	Work instruction	1	Visual inspection	2	10	20
35	Incomplete document created	Possible collision on the real machine tool	10	Required variables not defined	Work instruction	1	Visual inspection	2	10	20
Function: Export of the tool data										
36	No data exported	Generation of the set-up list not possible	2	Typing error	Work instruction	1	Visual inspection	1	2	2

A.2.5. Tool Dispensing System

Table 30.: PFMEA - Risk Analysis of the Tool Dispensing System
Source: Own illustration.

Nr.	**Potential failure**	**Potential effect(s) of failure**	**S**	**Potential cause(s) of failure**	**Current preventive action**	**O**	**Detective action**	**D**	**SxO**	**RPN**
Function: Storage of components and complete tools										
37	Components slip into the wrong compartment	Storage location is displayed incorrectly	3	Too many/less components per compartment	Work instruction	1	Visual inspection	2	3	6
38	Storage location entered incorrectly	Storage location is displayed incorrectly	3	Typing error	Work instruction	2	Visual inspection	2	6	12

Function: Display of the storage locations										
39	Barcode not recognized	Storage location is not displayed	3	Use of paper	Use of tablets	1	Visual inspection	1	3	3
Function: Calculation of the stock of the tools										
40	Stock entered incorrectly	Stock is displayed incorrectly	2	Typing error	Work instruction	2	Visual inspection	2	4	8
41	More tools than specified removed	Stock is displayed incorrectly	3	General error	Work instruction	2	Visual inspection	2	6	12

A.2.6. Set-up Area

Table 31.: PFMEA - Risk Analysis of the Set-up Area
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Function: Assembling of tool components into complete tools										
42	Tools assembled in the wrong length	Possible collision on the real machine tool	10	Human error	Work instruction	2	Presetting device	1	20	20
43	Complete tools assembled with the wrong components	Possible collision on the real machine tool	10	Human error	Work instruction	2	Presetting device	1	20	20

A.2.7. Presetting and Measuring Machine

Table 32.: PFMEA - Risk Analysis of the Presetting and Measuring Machine
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Function: Measuring of complete tools										
44	Tool measured incorrectly	Wrong measured value forwarded	4	Tool not dusted off	Work instruction	2	Visual inspection	2	8	16
	Tool measured incorrectly	Possible collision on the real machine tool	10	Wrong measuring method selected	Work instruction	1	Visual inspection	2	10	20
Function: Data transfer of the measured values										
45	Measured values saved in wrong format	Possible collision on the real machine tool	10	Wrong machine tool selected	Work instruction	1	Visual inspection	2	10	20
46	Label attached incorrectly	Machine tool cannot read in measured values	5	Human error	Work instruction	1	Visual inspection	2	5	10

A.2.8. Machine Tool

Table 33.: PFMEA - Risk Analysis of the Machine Tool
Source: Own illustration.

Nr.	Potential failure	Potential effect(s) of failure	S	Potential cause(s) of failure	Current preventive action	O	Detective action	D	SxO	RPN
Function: Loading data by SFC										
47	Data incomplete	Possible collision on the real machine tool	10	Data was released incompletely	four-eyes release process	1	Visual inspection	2	10	20
48	Wrong data loaded	Possible collision on the real machine tool	10	Wrong SFC search	Work instruction	1	Visual inspection	2	10	20
Function: Loading measured values of the tools										
49	QR-code not recognized	Possible collision on the real machine tool	10	Different possibilities	Work instruction	2	Visual inspection	1	20	20
Function: Setting up complete tools										
50	Measured values assigned to wrong tools	Possible collision on the real machine tool	10	Typing error	QR-code	1	Visual inspection	6	10	60
Function: Setting up clamping devices										
51	Wrong clamping devices selected	Possible collision on the real machine tool	10	Human error	Work instruction	1	Visual inspection	1	10	10

52	Wrong position of the clamping devices	Possible collision on the real machine tool	10	Human error	Work instruction	2	Visual inspection	1	20	20
Function: Setting up raw materials										
53	Wrong position of the raw material	Possible collision on the real machine tool	10	Human error	Work instruction	2	Visual inspection	1	20	20
54	Wrong raw material selected	Possible collision on the real machine tool	10	Human error	Work instruction	1	Visual inspection	2	10	20
Function: Setting up zero points										
55	Zero points deviate too much from the digital ones	Possible collision on the real machine tool	10	Human error	Work instruction	1	Visual inspection	2	10	20
Function: Loading the NC code										
56	Wrong NC code loaded	Possible collision on the real machine tool	10	Human error	Work instruction	2	Visual inspection	1	20	20
Function: Execution of the manufacturing process										
57	Speed and feed set incorrectly via potentiometer	Wrong machining data can be used	6	Human error	Work instruction	2	Visual inspection	2	12	24