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System benchmark of CAD-CAM in the area of tool making

CAD-CAM Systembenchmark im Werkzeugbau

Juan Calejero Martínez

Matrikelnummer: 11806533

Institut für Fertigungstechnik
Univ.-Prof. Dipl.-Ing. Dr.techn. Franz Haas

Technischen Universität Graz
Fakultät für Maschinenbau und Wirtschaftswissenschaften

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Abstract

In the following thesis a benchmark for CAD/CAM systems in the area of tool making is explained. This benchmark is adapted to the specific requirements existing in a hot-forging company located in the region of Styria (Austria). The mid-sized company demands an improvement of the current software situation to enhance the efficiency of the CAD/CAM processes and its landscape towards future digitalization processes.

Due to the broad spectrum of CAD/CAM software systems existing in today's market, it might be challenging to choose one software system that really fits to the requirements.

In order to solve this situation, a benchmark is done. Out of this benchmark, two CAD/CAM software systems were considered as future potential alternatives based on the requirements existing at the company. Then, a decision-making procedure made of five different scenarios and based on certain criteria is proposed. These five different scenarios are the combination of the current software systems existing at the Styrian forging company and the alternative software systems.

Kurzfassung

In die folgende Masterarbeit ist ein Systembenchmark für CAD und CAM Softwaresysteme im Werkzeugbau erläutert. Diese Systembenchmark anpasst für die spezifische Anforderungen, die es in eine Warmschmiedenunternehmen gibt. Der Standort des Unternehmens ist Steiermark (Österreich). Die mittelständigen Unternehmen verlang eine Verbesserung des aktuelles Softwaresituation, um die Effizienz des CAD und CAM Prozessen zu erhöhen und seine Landschaft in dir Richtung von zukünftigen digitalisierenden Prozessen.

Wegen des breiten Spektrums von CAD und CAM Softwaresysteme, die es in heutige Marktumfeld gibt, ist es eine anspruchsvolle Tätigkeit eine Softwaresysteme zu wählen, die alle Anforderungen richtig passen.

Um diese Situation zu absolvieren, eine Systembenchmark is erledigt. Aus der Fülle dieses Benchmarks, zwei Softwaresystemealternativen sind als zukünftigen potenziellen Alternativen für die Anforderungen, die in Unternehmen gibt, betrachtet. Danach, ist eine Entscheidungsfindungprozess aus fünf unterschiedenen Szenarien vorgeschlagen und auf bestimmten Kriterien basiert. Diese fünf Szenarien enthalten alle die Kombinationen mit aktuellen Softwaresysteme und alternativen Softwaresysteme.

Inhaltsverzeichnis

Abbreviations

CAD: Computed Aided Design
CAM: Computed Aided Manufacturing
AHP: Analytical Hierarchy Process
ERP: Enterprise Resource Planning
CMM: Coordinate Measuring Machine
NURBS: Non-Uniform Rational B-spline Surface
CSG: Constructive Solid Geometry
NC: Numerical Control
HSC: High Speed Cutting

1. Introduction

1.1. Motivation

CAD/CAM software systems constitute a basic technology in today's industry and its use is more extended year after year. They have not just enhanced productivity in design and manufacturing, but they also influenced positively digitalization processes development.

Currently, due to high level of competition in industry and the increasingly economic globalisation, enterprises are forced to produce faster and more effectively. This previous statement requires to stay updated with the market trend, regarding the methods of design and manufacture. These updates, related to manufacturing, should provide shorter development times, higher levels of quality and flexibility while keeping reduced prices to customer.

The following thesis is motivated to offer a benchmark and a decision-making procedure based on different scenarios of CAD/CAM systems intended for tool making. This benchmark is suited to the specific requirements existing at a forging company located in the region of Styria (Austria).

1.2. Objective

Currently, in today's market there are many different CAD/CAM systems like: AutoCAD, CATIA, Creo (formerly Pro/Engineer), Siemens NX, Solid Works, Solid Edge, Esprit or Work NC. Some of them are specialized in certain functions or industries and others are more general solutions that could perform reasonably well in all ambits. Given that, the main question handed at most technological companies is not only how to analyse which alternative fits better the current requirements, but also, which alternative would be most adapted towards future digitalization trend. This decision-making procedure tends to be critical and should be based on deep research.

The aim of this thesis is to provide a benchmark, and a decision-making procedure, of CAD/CAM software systems in the area tool making. Finding the solution that fits better to the current requirements and to the future digitalization requirements. The Styrian forging company needs to determine if the current situation could be improved by acquiring some alternative software system, either from changing only CAD, only CAM or both of them.

After doing a pre-benchmark of 49 systems, the scope of the benchmark was limited to two different software systems, which are referred in the following thesis as the alternative software systems, these are: Siemens NX, as the first alternative that provides CAD/CAM functionalities, and Esprit, as the second alternative that provides just CAM functionalities. More detailed information regarding the pre-benchmark is provided at the Benchmark Excel Sheet in the Appendix.

In order to implement the decision-making procedure, five scenarios were proposed. These are obtained from the combination of the current software systems, CATIA V5, ANSYS 3D SpaceClaim, Work NC and EdgeCAM, and the alternative software systems mentioned previously.

The evaluation of the scenarios is done from an objective and a subjective point of view. Regarding the objective side, the criteria evaluate not only the efficiency and functionality of the scenario but also the suitability towards future implementation of digitalization processes that might needed in the following years. Regarding the subjective side, it includes the opinion from the Styrian forging company's specialists of the alternative software systems in comparison to current software systems. This evaluation is based on the AHP method, later explained in State of the Art chapter. Afterwards, results will be presented to the Styrian forging company to assist their final decision whether staying with the current situation or selecting one of the possible future scenarios.

2. Technical background

In this following chapter an introduction to CAD/CAM is given.

As mentioned in Objective, the aim of this thesis is to provide a benchmark and a decision-making procedure of CAD/CAM software systems in the area of tool making, hence it is useful to comment some aspects of these software systems as a technical background.

2.1. Computed Aided Design (CAD)

CAD systems, used for mechanical design, enable the user to transfer ideas from the design of a product to a virtual geometric model through interactive graphs and sketches. This model can be in 2D, 2.5D or 3D depending on CAD system's capacity and the complexity of the piece to design. [1]

With 2D CAD design capabilities is possible to represent planar pieces designs when there is no need to give information regarding thickness but usually the most complex pieces and assemblies do require 3D CAD design capabilities mainly. [1]

When using 3D CAD design capabilities, the designer is able to transmit the idea created in his mind to the computer easier, as it is possible to view different perspectives and angles and does not need to work simultaneously in different side views like in the 2D CAD case. Additionally, when working on a complex assembly including different pieces it is easier when working on a 3D CAD, otherwise, understanding of design becomes tougher. Moreover, many 3D CAD software systems offer additional information regarding physical properties such as weight, centre of gravity, inertial momentum, volume… [1]

Regarding 3D CAD modelling techniques, any piece geometry designed with a 3D CAD is based on the following different modelling techniques: wireframe modelling, surface modelling, solid modelling, hybrid modelling or feature-based modelling.

2.1.1. Wireframe modelling

When using this technique, the piece is based on a finite number of points and edges that connect them, either curved or straight. The result is a model that represents the real shape of the object. This 3D CAD modelling technique is the easiest one from the geometric representation standpoint and additionally it requires minimum hardware computational effort to generate it. Nevertheless, it comprises some disadvantages when comparing to other modelling techniques such as, ambiguity of its representation, when representing complex pieces

2.1.2. Surface modelling

The real interest for surface modelling started when it was necessary to model great continuous surfaces with top quality requirements, mainly for automotive and aeronautic industry. Regarding the different surface types that are frequently used, they are briefed in the following paragraphs.

Bézier surface: Based on a polygonal network, in this type of surfaces it is possible to displace the nodes to modify tangents' directions and angles at edges and hence modify the surface. However, it is not possible to locally modify the shape of the surface and discontinuities are not possible. It approximates given input data (nodes) as it does not pass through all given data points. [1]

B-Spline surface: Based on a polygonal network, in this type of surfaces it is possible to displace the nodes to modify tangents' directions and angles at inner points of the surface and hence modify the surface. Moreover, it is possible to locally control the shape of the surface and the existence of discontinuities. It can approximate or interpolate given input data (nodes). [1]

Coons Patch surface: Coons patch is used to create a surface using curves that form closed boundaries. [1]

Draft surface: Useful for demoulding surfaces modelling. [1]

Fillet surface: Useful to blend two surfaces seamlessly [1]

Gordon surface: Generated from a contour line map placed in two different directions. [1]

NURBS (Non-Uniform Rational B-spline Surface): Enables surface representation using mathematical formulas. Useful for any kind of surface type. [1]

Offset surface: Already existing surfaces can be offset to create new ones, identical in shape but they may have different dimensions. [1]

Planar surface: Three non-coincident points are required to define an infinite plane. The plane surface can be useful for generating cross-sectional views by intersecting a surface model with it, generate cross sections for mass property calculations, or other similar applications where a plane is needed. [1]

Ruled surface: Generated from the displacement of a straight line whose limits intersect with two curved lines, named as boundary curves. [1]

Revolution surface: Axisymmetric surface that can model axisymmetric objects. It is generated by rotating a planar wireframe entity in space around the axis of symmetry in a certain angle. [1]

Sweep surface: Generated by the displacement of a curve along a trajectory. [1]

Tabulated surface: Obtained by translating a planar curve a certain distance along a certain direction (axis of the cylinder). [1]

Freeform surfaces: They do not have rigid radial dimensions, unlike regular surfaces such as planes, cylinders and conic surfaces. The shapes of freeform surfaces are expressed by their poles, degree or term order, and number of patches (segments with spline curves). [1]

The degree determines its mathematical properties and represents the shape by a polynomial with variables to the power of the degree value. For example, a surface with a degree equal to one is a flat cross section surface, a surface with degree equal to two is curved in one single direction, whereas in a degree equal to 3 the surface changes once from concave to convex curvature.

The poles (also named as control points) of a surface define its shape. The natural surface edges are defined by the positions of the first and last poles. The intermediate poles act like magnets pulling the surface in their direction. However, the surface does not go through these points. The second and third poles as well as defining shape, respectively determine the start, tangent angles and the curvature.

In a single patch surface, called as Bézier surface, mentioned previously, there is one more pole than degree values. Surface patches can be merged into a single NURBS surface at knot lines. The number of knots will determine the poles influence on either side and the smoothness of transition. The smoothness between patches, known as continuity, is often referred to in terms of a C-Value: zero “C0” just touching, one “C1” tangent but could have a change in curvature, two “C2” patches are curvature continuous to one another [2].

2.1.3. Solid modelling

CAD systems use several schemes of solid modelling representation. Most common ones are: CSG (Constructive Solid Geometry), B-Rep (Boundary Representation), Hybrid Modelling and Feature Based Modelling.

CSG (Constructive Solid Geometry): Starts with pre-existing solids, named as primitive solids, these are modified with certain operations such as union, intersection and difference.

The main disadvantage of this modelling technique is the inability of designing complex pieces based on primitive shapes. [1]

B-Rep (Boundary Representation): based on the idea that any solid object is restricted to a finite number of sides, whose are limited to a finite number of edges defined at the same time by their vertexes. Sides can be planar or curved, but the most extended idea is to approximate those curved surfaces (curved sides) with discrete elements (meshes) of planar polygons. This enables to represent really complex shapes. [1]

2.1.4. Hybrid Modelling

This technique uses a mixture of wireframe, surface and solid modelling. Inside a hybrid system, it is likely to find surface and solid functions. The piece can be defined as many surfaces and once is a closed volume, it becomes a solid. Or the other way, it can start as a solid that temporarily can become a surface when one of its sides need to be modified or replaced. With hybrid modelling, boolean operations work on both types of geometry, which opens new possibilities during designing [3].

2.1.5. Feature-based Modelling

A feature is the basic unit of a parametric solid model. Feature-based Modelling refers to the construction of geometries as a combination of form features. Historically, this concept of feature was introduced for the process planification of machined pieces. In many process planification systems, these features were used to characterise the machined surfaces of the volumes in several operations. Currently, these feature characterisations based on features have become crucial for data interchange between design and manufacturing areas. The designer specifies features in engineering terms such as holes, slots, or pockets rather than geometric terms such as circles or cylinders. However, features can also store nongraphic information, this information can be used in activities such as drafting, NC-Codes, finite-element analysis, and kinematic analysis. Furthermore, feature-based packages frequently record the geometric construction and modification sequences used in building the model. [1]

For example, when defining a slot as a boolean difference between the part and space. When not using feature-based modelling, the problem was that lengthening the part geometry turns the slot into a blind hole. But when using feature-based modelling method, through-hole feature understands that it must pass through the part, no matter how the part changes.

2.2. Computed Aided Manufacturing (CAM)

CAM systems are those tools that assist users to generate the needed instructions, named as NC-Code, to manufacture components or machined products. These modules have evolved widely in the past ten years, enabling to simulate, in a very realistic way, chip removal from initial product shape. With this simulation it is possible to check intermediate states of product shape in between machined steps or operations, enabling to detect non-machined areas during chip removal process. Moreover, these modules include tools for collision detection between working place elements like tools, clamping devices, machine and/or spindles, furthermore it includes operation time estimation. This last feature is very important as it enables to compare and check times for different machining strategies in the process of mechanization. [1]

Regarding the input data that CAM systems require, basically these software systems need the geometry of the piece. This geometry can be provided from a CAD module integrated with the CAM software or it could be delivered from another independent CAD or CAD/CAM module. [1]

When using a complete CAD/CAM solution, the problems dealing with geometrical information transference or data translation are drastically reduced. However, there are also independent CAM systems inside the market, which force to export the geometry from CAD software system and import it in the CAM solution. Usually these export/import processes are made with .iges, or .step data formats. [1]

Another possibility, enables to introduce the geometrical information from a point cloud. This corresponds to the surface of the piece and is obtained from a previous measuring process in a Coordinate Measuring Machine (CMM). The quality of the final surface depends on the density of the mentioned point cloud. This method is very common in mold construction for polymer injection, where the process begins with a physical model of the piece. [1]

Apart from CAM systems, there are additional tools currently in the market specific for simulation after postprocessor, these tools are called Digital Twins.

3. Enterprise Situation

In this chapter an introduction to the Styrian forging company situation is given.

Some general information regarding historical background of the company and some data regarding the current manufacturing process is provided in Enterprise information subchapter.

Next, in Current software situation subchapter, the current software situation and the information flow diagram, named as spaghetti diagram, between client and manufacturing process is presented. Additionally, this subchapter presents the software tools that are needed in the process in current situation. More detailed information regarding software tools is provided in the Function Comparison Tables in the Appendix.

Afterwards, in Future possible scenarios subchapter, as there are two software system alternatives inside the scope of the project, five different future possible scenarios are defined. These scenarios consider all the possible combinations of current software systems and alternative software systems.

Additionally, Future possible scenarios subchapter, briefly introduces the software tools from the alternative software systems. These are the equivalent tools to those tools presented in the current software systems. More detailed information regarding alternative software system tools is provided in the Function Comparison Tables in the Appendix.

Lastly, in Analysis of direct competitors subchapter, an overview about the current situation regarding CAD/CAM software systems from the direct competitors of the Styrian forging company is given.

3.1. Enterprise information

This enterprise, which is the main protagonist of this thesis and spotlight of the CAD/CAM benchmark application, is located in the region of Styria (Austria). It is a mid-sized enterprise with approximately 300 employees.

The company has a long tradition in hand-tools forging, around 300 years of experience, but in 1980 they decided to launch different products to market, mainly for automotive industry. Today, thanks to its main customer in Austria, which is an important automotive company, their forged parts are found in almost every premium car, buses and trucks. Moreover, it also offers parts for the construction industry.

Regarding product data, the variability in terms of design, shapes and sizes is huge. This enterprise is asked to improve an existing part or design a new part each two days, this means that the flexibility and adaptability of processes need to be ensured as there is no possibility of standardization. In average, the Styrian forging company introduces around 100 new parts each year to their catalogue.

Inside the company facilities, there are ten manufacturing lines to forge the parts. Each line has a hot-forging die, where there are three employees performing the necessary movements to rotate the part and place it at the exact position to forge it properly.

Afterwards, depending on the specific requirements of the part, they are heated up in a thermal process up to a certain temperature to assure specific material properties. Next, the parts are cooled down and carried to the verification area. In this verification area, the parts are carefully examined to assure the quality of the piece and reject those parts that do not satisfy the requirements.

After all this manufacturing process, the forged parts are stored and sent to the customer.

3.2. Current software situation

Firstly, it is necessary to present the workflow of this enterprise, from customer order until manufacturing. In order to have a clearer view of the current software situation, a spaghetti diagram was made. The diagram, shown in **Figure 3.1**, represents the information flow between departments and software systems

Customers contact with the enterprise and request for a specific forged part. This information is provided to the forging die design department as a technical sketch or drawing (.pdf), or seldomly as a virtual model in 2D data format or 3D data format. This virtual model represents the shape of the final part when forged, but in order to create the forged part, it is necessary to design the forging die for this specific part.

The forging die is designed according to the dimensional and morphological requirements of the product and considering physical variables like material elasticity, pressing force, pressing power, temperature and thermal contraction.

This task of forging die design is carried out by the CAD department, where there are six employees. Basically, CAD designers create the forging die out of the forged part, like a negative-image model of the part itself, as it is the opposite shape.

This design is currently handed on with CATIA V5, more specifically CATIA V5 R26 SP4. This common product is very likely to find it in the automotive and aeronautic industry. It is provided by the company Dassault Systèmes.

In order to carry out the forging die design in a short time and in an efficient way, several functions mentioned in the Computed Aided Design (CAD) chapter are needed. For example, solid modelling, surface modelling, and especially freeform shape modelling.

Afterwards, when this forging die is designed, fulfilling all the basic design requirements and with the from the customer, the forging die is simulated in a forging process simulation software system called DEFORM (Design Environment for Forming). This software is provided by the company Scientific Forming Technologies Corporation. It provides a useful software system to check some parameters to assure that the process is physically feasible in terms of temperature distribution, pressing force and material flow through the forging die. Then, all data are stored in the Project Folder, in their respective data formats.

The data from CAD department are saved in the Project Folder and then this data are opened in the CAM department. In this department, there are four programmers who examine the current forging die design and choose the most suitable solution for its manufacturing process. In order to manufacture the forging die, there are several machines at the shopfloor such as: lathes, HSC (High Speed Cutting) 3-Axis milling machines or 5-axis milling machines.

In order to provide an effective and efficient manufacture of the forging die from a raw cylindrical piece of steel, two software systems are used Work NC and EdgeCAM. Both software systems are provided from the same supplier, Vero Software.

To complete the NC-Code programming task, tools and procedures such as automated feature recognition, contour machining and rest manufacturing are used. Sometimes the programming requires both software systems or just one of them, whether it starts in EdgeCAM and then finished in Work NC, or vice versa.

When starting with EdgeCAM, data are imported as .step format, which is a 3D data format. There is no direct link between CATIA V5 and EdgeCAM, therefore CAD files need to be imported through ANSYS 3D SpaceClaim. In this ANSYS 3D SpaceClaim, some changes in design regarding radii are made for a convenient manufacturing process. Then, the data are imported as .scdock data format from ANSYS 3D SpaceClaim into EdgeCAM.

In the other way, when starting with Work NC, data are imported as .iges format. In Work NC programmers are able to do all radii modifications, as it contains intern CAD functionalities.

During all this process there are numerous export/import operations and data translations where some data might be damaged and lost. This is one of the drawbacks presented at the current software situation.

Roughly, regarding the purpose of the different software systems, Work NC is more intended for milling operations and complex operations and EdgeCAM is more intended for easy tasks, feature recognition functionalities and some turning operations. This is another drawback of the current situation, all these functionalities could be included in just one system instead of having them divided in two separate software system.

Furthermore, one additional inconvenient of the current software situation is that there are two main CAM software systems. This scene leads to require two different postprocessors for each machine. Nevertheless, the situation could be improved by replacing these two software systems with one single CAM software and hence, just one postprocessor.

Another hindrance of this workflow between CAD and CAM department, in the current situation, is that it is possible to need some rework. For example, when the proposed forging die design does not match with the available space inside the milling machine volume, it is necessary to readapt the design to avoid collisions with the spindle or the tool.

Regarding the next steps of the process, once the NC-Codes are generated, all these data are sent to shopfloor.

These data, included in Project Folder, contain the generated NC-Codes previously mentioned, a 3D virtual model of the forging die (just to view the current shape of the piece but without the ability to make changes in the design) and the “Einstellblätter”. This “Einstellblätter” contains, mainly, all instructions for the different operations regarding type, diameter and length of drill bit required, and the required clamping system. These data are generated and exported from Work NC and EdgeCAM.

Depending on which machine is needed, HSC 3-Axis or 5-axis, the importing process in the machine is done via TNCremo (as a middleware solution to transfer files) or via Server.

Some forging dies might require an additional task, like letter or number engraving. This is programmed at shopfloor by operator using VectorCAM.

Additionally, it is planned to include NCSimul, previously commented in Computed Aided Manufacturing (CAM) subchapter.

When forging dies are ready, they are sent to the manufacturing line where they are used to shape final forged parts.

There are two additional software systems in the current software situation, both of them are outside of the project scope. First one, is the ERP solution, called Jet Orbit, and the other one is the production controlling software, Proxia.

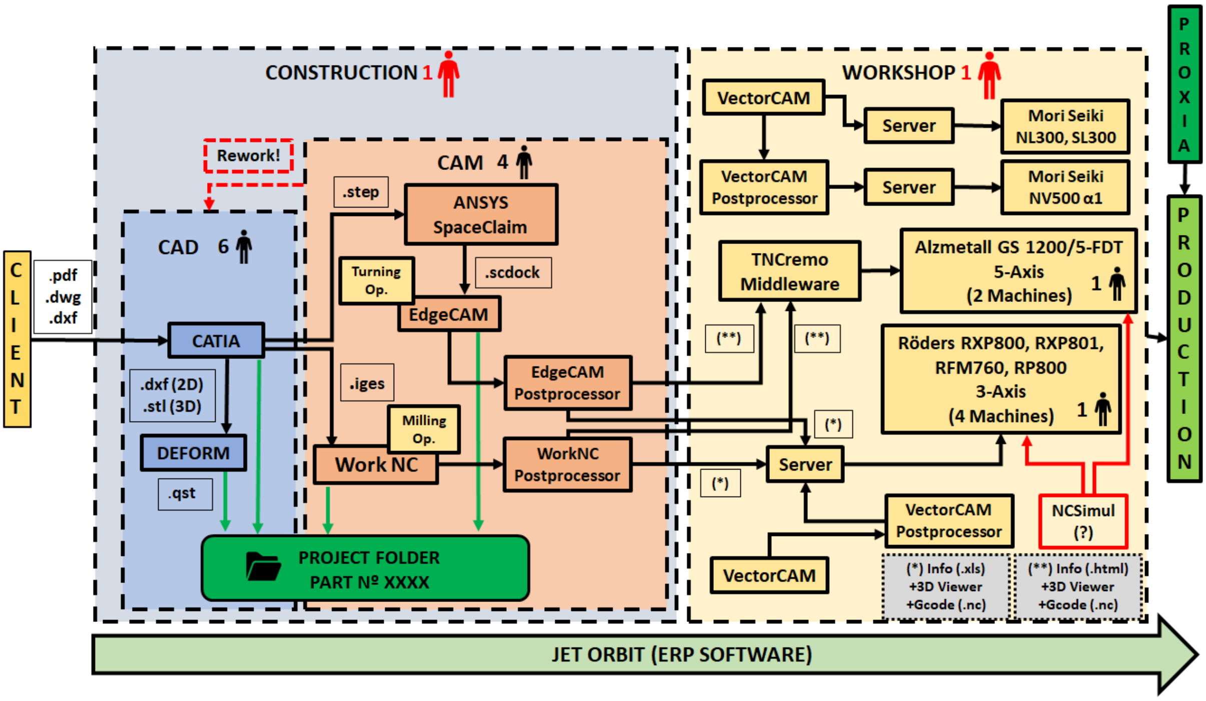


Figure 3.1: Current software situation

3.2.1. CATIA V5

Current version from this software system is CATIA V5 R26 SP4. The tools used at the enterprise for forging dies design are shortlisted in **Table 1**. The information was obtained from [4]. More information regarding these tools is provided in Function Comparison Tables, see Appendix.

Table 1: Current tools used in CATIA V5

Current tools used in CATIA V5
Assembly Design (ASD)
Part Design (PDG)
Wireframe & Surface 1 (WS1)
Generative Drafting 2 (GDR)
Generative Shape Design 2 (GSD)

3.2.2. Work NC

Current version from this software system is Work NC 2018R1 SU2. The tools used at the enterprise for forging dies manufacture programming are shortlisted in **Table 2**. The information was obtained from [5]. More information regarding these tools is provided in Function Comparison Tables, see Appendix.

Table 2: Current tools used in Work NC

Current tools in used Work NC
Viewer WNC-VW
Work NC CAD WNC-CAD
Work NC Full License WNC-FL
Auto5 WNC-MA5
5 Axis Post-Processor WNC-P5XCS
Extra Workzone Calculation Window WNC-O3XP
Advanced Parallel Processing WNC-APL
Extreme Parallel Processing WNC-EPL

3.2.3. EdgeCAM

Current version from this software system is EdgeCAM 2016R2 SU14. The tools used at the enterprise for forging dies manufacture programming are shortlisted in **Table 3**. The information was obtained from [6]. More information regarding these tools is provided in Function Comparison Tables, see Appendix.

Table 3: Current tools used in EdgeCAM

Current tools used in EdgeCAM
EdgeCAM Milling
EdgeCAM Turning
EdgeCAM Waveform
EdgeCAM Part Modeler
EdgeCAM Intelligent Manufacturing Workflow
EdgeCAM Solid Machinist
EdgeCAM Strategy Manager

3.3. Future possible scenarios

As a result of the pre-benchmark process, 49 companies were contacted. These systems were researched regarding the following criteria: CAD/CAM solution, german language version available, milling 2, 3, 4, 5-axis, turning, high speed machining, additional functions or specific package for forging companies, type of license, installation service, support/maintenance, test version available. More information regarding this pre-benchmark is available at the Benchmark Excel Sheet at the Appendix.

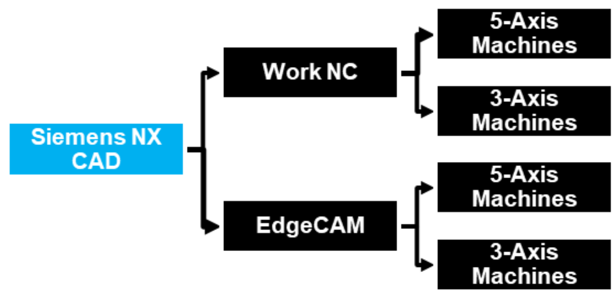
After this pre-benchmark process, it was decided that the alternative software systems included in the scope of the benchmark would be Siemens NX and Esprit, due to the following reasons:

- Siemens NX for being a complete solution that provides CAD/CAM functionalities and also very popular in the CAD/CAM software system market.
- Esprit for being a specific software system for CAM functionalities and with an already proved efficiency in the Institute for Production Engineering at Technical University of Graz.

With these alternatives, then, it is possible to think of several scenarios combining software systems from the current software situation and alternative software systems. These are presented in the Table 4.

It includes in black colour the already existing software programs at the Styrian forging company and in blue the new software programs:

Table 4: Future possible scenarios

Future possible scenario	CAD/CAM combination
Future possible scenario I: CATIA V5 + Esprit (New CAM software system)	
Future possible scenario II: CATIA V5 + Siemens NX CAM (New CAM software system)	
Future possible scenario III: Siemens NX CAD + Esprit (New CAD/CAM software system)	
Future possible scenario IV: Siemens NX CAD + Siemens NX CAM (New CAD/CAM software system)	
Future possible scenario V: Siemens NX CAD + Work NC + EdgeCAM (New CAD software system)	

Additionally, the spaghetti diagrams for each future possible scenario are presented in Appendix.

3.3.1. Siemens NX

Current version from this software system is Siemens NX. The potential tools that could substitute the tools from current software systems, see CATIA V5 section, Work NC section and EdgeCAM section, are shortlisted in Table 5. [7]

CAD tools are presented in blue colour and CAM tools are presented in orange colour.

Table 5: Tools in Siemens NX

Tools in Siemens NX
NX (Advanced) Assembly
NX for Design
NX Freeform Modelling
NX Drafting
NX Shape Design
NX Viewer
Complex Parts Machining
Mold, Die & Electrode Machining
Prismatic Parts Machining
NX Adaptive Milling
NX Turning
5-axis Machining
Postprocessing & Machining Simulation
Parallel Generate
FBM Package (Feature Based Manufacturing)

These previous tools are the equivalent tools to those existing in the current software systems (CATIA V5, Work NC and EdgeCAM). These functions will be compared to current ones in the Own approach chapter. More information regarding these tools from Siemens NX is provided in Function Comparison Tables in Appendix.

3.3.2. Esprit

Current version from this software system is Esprit 2018R3. The potential tools that could substitute the tools from current software systems, see Work NC section and EdgeCAM section, are shortlisted in **Table 6**. The information was obtained from the software reseller of Esprit.

CAD tools are presented in blue colour and CAM tools are presented in orange colour.

Table 6: Tools in Esprit

Tools in Esprit
Viewer from ESPRIT
Intern CAD from Esprit
SolidMill Production Package
SolidMill Freeform 3-Axis
ProfitMilling
SolidTurn Package
SolidMill Freeform 5-axis
Standard Postprocessor & Simulation
Parallel Processing
CheckItB4 First Step
Automated Feature Recognition, FX Technology
KnowledgeBase

These previous tools are the equivalent tools to those in the current software systems (Work NC and EdgeCAM). These tools will be compared to current ones in Own approach chapter. More information regarding these tools from Esprit is provided in Function Comparison Tables in Appendix.

3.4. Analysis of direct competitors

In the benchmark process the situation of direct competitors is considered.

The definition of a direct competitor is provided in the following: “a person or business who is competing with another to sell the same product or service” [8].

For this direct competitor analysis, nine companies were researched, all of them located in the middle Europe as shown in Figure 3.2.

Figure 3.2: Direct competitors ubication

Some information regarding the main products offered by the enterprise, their machines, the used CAD/CAM software systems and the number of employees is provided in the Table 7.

Table 7: Summary of direct competitors

	Styrian Forging Company	Unior	Hirschvogel	KB	voestalpine Böhler	Omco	MolDesign	HWB	Penn	Bernhofer
Mitarbeiter	> 300	1793	386	120	2171	1700	k.A.	30	1000	150
CAD	Catia V5, Ansys SpaceClaim 3D	Pro Engineer Creo, Catia V5, Siemens NX	Catia V5, Pro Engineer Creo Parametric, Siemens NX, Exapt	Pro Engineer Creo Parametric 3.0	Siemens NX	Catia V5, Pro Engineer Creo, AutoCAD, CorelCad, Siemens NX, TypeEdit	Siemens NX	Siemens NX	Autocad, Autodesk Inventor Professional, PTC Creo Parametric 2.0, Euklid	VISI CAD, AutoCAD
Anzahl	2	2	4	1	1	6	1	1	4	2
CAM	Work NC, EdgeCAM, VectorCAM	Siemens NX	Catia V5 Machining, HyperMill, Peps, Exapt	Euklid CAM V16	Siemens NX	Mastercam, Power Mill, CIMCO, Siemens NX, TypeEdit	-	PowerMill	Euklid	WorkNC
Anzahl	3	1	4	1	1	5	0	1	1	1

Unior, located in Zreče (Slovenia). Its products are forging components for chassis, connecting rods, hand tools for automotive purposes and sintered components like chains, pulley wheels and wheel flanges. Their machines perform operations like drilling, milling, turning, grinding, thrusting, broaching, reaming and polishing. Regarding its CAD/CAM software systems, they use Pro Engineer Creo, CATIA V5 and Siemens NX for CAD functionalities and Siemens NX for CAM functionalities. In total they are 1793 employees. [9]

From Denklingen (Germany), Hirschvogel Automotive Group. Its main products are electrical engines, chassis, gears, off-highway automotive components, power trains, motors, fuel injection systems and carrosserie. Their machines perform operations like sawing, milling, turning, grinding, sink and wire eroding and polishing. Regarding its CAD/CAM software systems, they use CATIA V5, Pro Engineer Creo Parametric, Siemens NX and Exapt for CAD functionalities and CATIA V5 Machining, HyperMill, Peps and Exapt for CAM functionalities. Additionally, they use SAP as an ERP software. In total they are 386 employees. [10]

From Hagen (Germany), KB Schmiedetechnik GmbH. Its main products are made of steel (including Duplex and Titanium) for industrial valves and fittings, boilers and pipes, valve components, pipe connectors, special flanges and hydraulic components. Regarding its CAD/CAM software systems, they use Pro Engineer Creo Parametric 3.0 for CAD functionalities and Euklid CAM V16 for CAM functionalities. Additionally, they use QForm V8 as a simulation software. In total they are 120 employees. [11]

The next enterprise is voestalpine Böhler Aerospace GmbH & Co KG, previously named Böhler Schmiedetechnik, located in Kapfenberg (Austria). Its main products are for aerospace and power generation purposes. Regarding its CAD/CAM software systems, they use Siemens NX for CAD functionalities and Siemens NX for CAM functionalities. Additionally, they use an own ERP software. In total they are 2171 employees. [12]

The next direct competitor is OMCO, located in Aalter (Belgium). Its main products are glass moulds and mould equipment. Regarding its CAD/CAM software systems, they use CATIA V5, Pro Engineer Creo, AutoCAD, CorelCad, Siemens NX and TypeEdit for CAD functionalities and Mastercam, Power Mill, CIMCO, Siemens NX and TypeEdit for CAM functionalities. Additionally, they use MagmaSoft for simulation. In total they are 1700 employees. [13]

The following competitor is MolDesign, located in Judenburg (Austria). Its main products are intended for the automotive industry, toy industry, household technology market, electric and electronic industry and furniture industry. Regarding its CAD/CAM software systems, they use Siemens NX. [14]

From Horitschon (Austria), HWB Horitschoner Werkzeugbau. Its main activities are mould making and injection moulding tools. Their machines perform operations of turning, CNC milling, HSC milling, flat grinding, sink and wire eroding. Regarding its CAD/CAM software systems, they use Siemens NX for CAD functionalities and Power Mill for CAM functionalities. Additionally, they use MoldFlow Insight Premium 2014 for simulation. In total they are 30 employees. [15]

Penn, located in Imbach (Austria). Its main products are intended for the automotive industry, construction industry, conveyor technology and railway technology. Their machines perform operations of milling, turning, HSC milling, eroding, wire cutting and polishing. Regarding its CAD/CAM software systems, they use Autocad (2D), Autodesk Inventor Professional, PTC Creo Parametric 2.0 for CAD functionalities and Euklid CAM for CAM functionalities. Additionally, they use Simufact Forming for simulation. In total they are 1000 employees. [16]

The last enterprise is Bernhofer Gesenkschmiede, located in Höhnhart (Austria). Its main products are intended for vehicle manufacturing, engine manufacturing, machine manufacturing and gear manufacturing for the agricultural market, conveyor technology and ropeway construction. Regarding its CAD/CAM software systems, they use VISI CAD, AutoCAD – LT for CAD functionalities and Work NC for CAM functionalities. In total they are 150 employees. [17]

From this analysis it was seen that the biggest potential is in the CAM department, as shown in the bubble diagram in Figure 3.3, where the number of software systems intended for CAM functionalities needs to be reduced at the Styrian forging company. Competitors are represented in red colour and the Styrian forging company in green colour. Bubble radii are drawn according to the number of employees in the company.

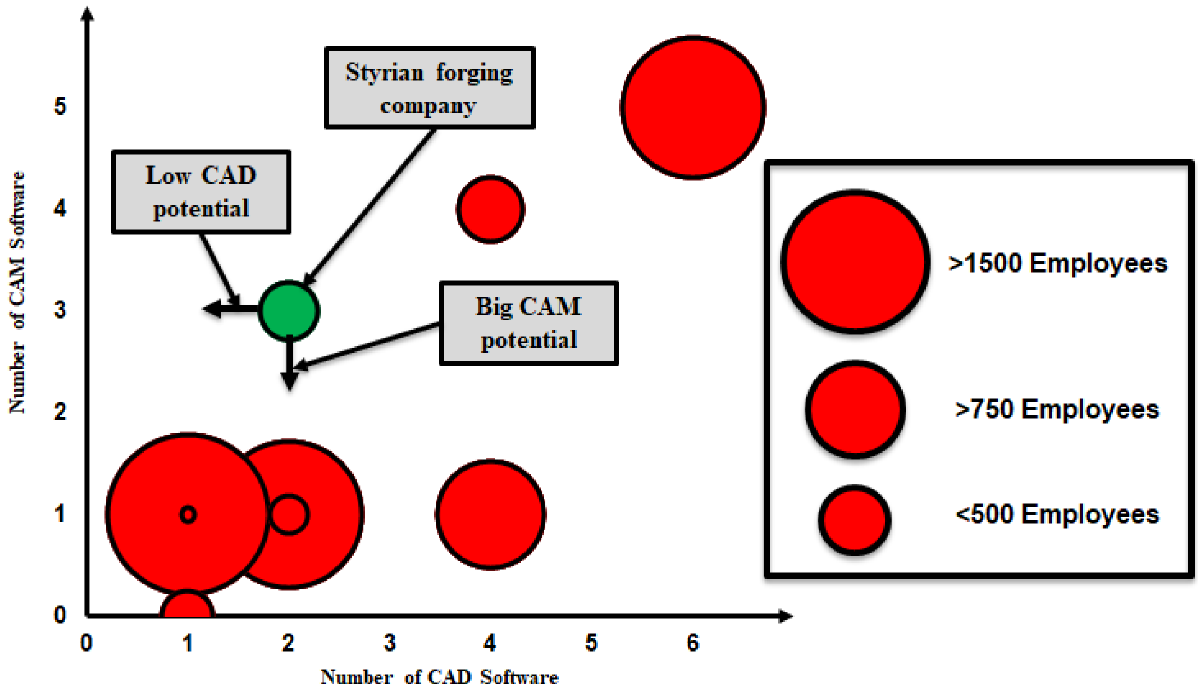


Figure 3.3: Competitors CAD/CAM software system situation

4. State of the Art

In this fourth chapter, two case studies for decision-making procedures in CAD/CAM benchmarks are reviewed. All the scientific papers, explained in State of the Art chapter, carried out their benchmark process based on the Analytic Hierarchy Process method, most known as AHP method.

First, a short explanation of the AHP method is given. Then, the studies that use the AHP method are presented. In these studies authors explain the situation from different companies that were in the same dilemma as the Styrian forging company. They needed to decide among many different software products, for CAD and/or CAM, to suit their specific requirements.

The Analytical Hierarchy Process, most known as AHP, was developed by Thomas L. Saaty [18]. This method has been found to be an effective approach that enables to handle with complex and unstructured decisions. It helps decision makers finding the alternative that best suits their goal regarding certain requirements. Hence, the output of AHP is a prioritized ranking, in percentage values, of the suitability of each alternative towards the end goal.

There are three main steps when using AHP method: hierarchy establishment, element weighting and consistency measurement.

The structure of the hierarchy descends from an overall goal to various criteria and subcriteria, and so on until the lowest level. The overall goal of the decision is represented at the top level of the hierarchy, the criteria and subcriteria contributing to the decision are represented at the mid-levels and lastly the alternatives are located at the lowest level of the hierarchy. For example, in **Figure 4.1** it is possible to find one main goal, two criteria (1) and (2), five subcriteria (1A, 1B) and (2A, 2B, 2C), and two alternatives, Alternative 1 and Alternative 2.

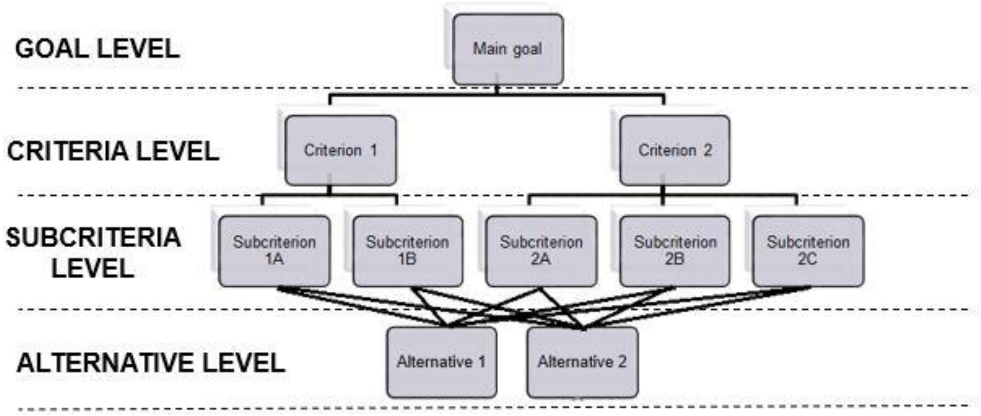


Figure 4.1: Example of AHP hierarchy

According to author from [19], a hierarchy can be done using creative thinking, data collection and brainstorming, when decision is made in a group. Author further notes that there is no standard procedure for generating the levels of the hierarchy. The structure of the hierarchy depends on the type of decision. Moreover, the number of the levels in a hierarchy depends on the problem complexity and the degree of detail of the problem.

Once the hierarchy has been fixed, the following step is to determine the importance of elements at each level. “Element” means every member of the hierarchy, could be either criteria, subcriteria or alternatives.

A set of pair-wise comparisons are made between all elements in a level of the hierarchy with respect to an element of the immediately higher level, this prioritizes and converts individual comparative judgments into ratio scale measurements.

The standard preference scale used in AHP is 1-9 scale which ranges from equal importance (1) to extreme importance (9), see Table 8.

Table 8: Scale of preference between two elements [19].

Preference weights/level of importance	Definition	Explanation
1	Equally preferred	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly favour one activity over another
5	Strongly	Experience and judgment strongly or essentially favour one activity over another
7	Very strongly	An activity is strongly favoured over another and its dominance demonstrated in practice
9	Extremely	The evidence favouring one activity over another is of the highest degree possible of affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromise between the preferences listed above
Reciprocals	Reciprocals for inverse comparison	

For example, in a two-elements comparison with “Element A” and “Element B”.

When measuring the preference of “Element A” over “Element B”, if the value is a 3 indicates that “Element A” is moderately preferred to “Element B”.

Likewise, the value of preference of “Element B” over “Element A” is 1/3, which indicates that “Element B” is moderately unpreferred to “Element A”.

All these comparisons are placed in the following matrix A, see Table 9. Obviously when comparing “Element A” or “Element B” with themselves, the preference value is 1, so the diagonal of the matrix always contains the same value of 1.

Table 9: Comparison matrix (A)

Comparison matrix	Element A	Element B
Element A	1	3
Element B	1/3	1

When the comparison matrix is completed, the rows are added for each column and a total score is obtained. Then each number of the matrix is normalized by dividing it with its respective total score. Lastly, all the values of each row are arithmetically averaged to calculate the importance rate, named as criteria or subcriteria weight vector (W).

It is possible to calculate for the previous result a consistency measurement, which is the third step. This procedure starts with the multiplication of the original comparison matrix times the weight vector (W), matrix product, to obtain the pondered weight vector (Ws). Then, the consistency vector (CS) is obtained by multiplying the pondered weight vector (Ws) times the inverse values from the weight vector (W), scalar product.

Afterwards, the values of the consistency vector (CS) are arithmetically averaged to obtain the maximum eigenvalue (λ_{max}). Then, consistency index (CI) is obtained by using equation 4.1. The value of N represents the dimensions of comparison matrix (A), which is (N x N).

$$CI = \frac{\lambda_{max} - N}{N-1} \quad (4.1)$$

Once the consistency index (CI) is calculated, the consistency ratio (CR) is obtained by using equation 4.2. RCI represents the random consistency index which is obtained from Table 10, depending on matrix A dimension (N x N).

$$CR = \frac{CI}{RCI} \quad (4.2)$$

Table 10: Random index value [19].

N	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

If CR value is below 0.1, the method is consistent and there were no mistakes inside the procedure [19].

In this State of the Art chapter, two research papers about CAD/CAM benchmarks are reviewed. The decision-making procedures of these papers are based on the AHP method.

One of the most critical tasks when implementing AHP method is deciding based on which criteria and subcriteria compare the different alternatives. In the first research [20], the AHP method is used as a decision-making technique for identifying and prioritizing important factors for CAD/CAM software system selection. This methodology has been thought to represent one of the most promising approaches to multicriteria decision-making problems. [20]

This research is oriented to analyse and evaluate current criteria for selecting a CAD/CAM software system for small- to medium-sized manufacturing companies in Pakistan. However, unfortunately, there are many difficulties when selecting a CAD/CAM software system for industries in a developing country like Pakistan, as these industries are operating at a very low budget and have insufficient expertness to analyse and decide which software to purchase. [20]

Authors from mention that CAD/CAM software systems have assisted pakistani companies in design and manufacturing for many years, nevertheless many companies are using obsolete packages to design and manufacture products due to the fact that technology is changing very rapidly, and most companies cannot keep up with the updates. These pakistani companies should be informed about what types of CAD/CAM software systems are available in the market but they do not have the time or the abilities to perform in-depth research in seeking out new tools for aiding their design or manufacturing processes. Moreover, companies also need to know what criteria are important in selecting a CAD/CAM software system. [20]

The task-storyline that was followed in this research, can be briefed as follows: benchmark of CAD/CAM software systems available in today's market, selection of important criteria by authors when selecting CAD/CAM software systems and weighting of these previous criteria using AHP method. [20]

In the scope of the research fifteen companies were analysed. Three different CAD software systems were being used within the fifteen companies and, out of those fifteen only twelve were using a CAM software system associated with their CAD software system. [20]

Regarding the hierarchy of the AHP method, there were ten criteria and no subcriteria. These ten criteria were: price, communication, capabilities, functionality, import/export, operating system, expandability, after-sale support service, efficiency and analysis. It is necessary to remark that none of those criteria were decided in collaboration with the companies, authors decided to provide them fixed to enterprise evaluators. [20]

Results of the AHP method were that, companies seemed to be more interested in buying CAD/CAM software systems that are efficient within reasonable price having good communication properties on network management. [20]

On the plus side, the output of this research paper is that efficiency in the functions of the software tools tends to be one of the most important criteria when selecting a CAD/CAM software system, however it could be interesting to consider other aspects.

On the down side, this research does not give a detailed explanation about the mentioned criteria, for example, in terms of clearly defining what "functionality" or "capabilities" criteria comprise, additionally, it does not offer any subcriteria. Moreover, it does not provide results regarding the CAD/CAM software system that was chosen, it only provides the numerical results from the weighting of mentioned criteria.

In order to contrast with the tasks from previous research, this research [21] utilize the same AHP method, however, the criteria and subcriteria were better defined. They were selected with the help of many literature survey and in collaboration with the industrial experts of the small manufacturing firm were AHP method was implemented. This small enterprise was located in the state of Andhra Pradesh (India). [21]

By using a questionnaire, the feedback of the company about CAD/CAM software systems was fully understood. The main idea of the top-management was planning to implement a CAD/CAM software system in order to improve the design and high-speed manufacturing processes. With the help from questionnaires, and some collaborative workshops between authors and top-management, a complete list of eight criteria and 34 subcriteria was obtained. [21]

On the plus side, as a conclusion, this research paper [21] points out that the application of AHP method, in the CAD/CAM software system benchmarks for the manufacturing firms, does improve the team decision-making process. This AHP method reduces the amount of time required for the selection of suitable software systems regarding some main criteria and subcriteria and enables decision makers to take an appropriate decision. Moreover, the criteria and subcriteria should take into consideration the opinion of the company and not just the authors' opinion.

On the down side, this paper does not consider that, although the industrial experts of the enterprise may have a lot of experience using CAD/CAM software systems, there were many people involved in the decision of criteria and subcriteria, which leads to a wide variety of different opinions or judgements. This much number of opinions create uncertainty when mapping people's judgement to a number in between the wide range of the AHP method, in other words, it is hard to differentiate between moderately (3), strongly (5), very strongly (7) or extremely preferred (9).

After this literature survey, the following drawbacks from implementing the AHP method in CAD/CAM benchmarks emerged:

- The vagueness and uncertainty on judgments of the decision-makers in the AHP method seems to insufficient and imprecise to capture the right judgments of decision-maker [22].
- It deals with a very unbalanced scale of judgment [22].
- The subjective opinion, in terms of selection and preference of decision-makers, has a great influence on the results [22].
- Although some (sub)criteria could be equal for CAD and CAM software systems, there should be some specific (sub)criteria for CAD and for CAM software systems. An optimal (sub)criteria definition creates a clearer pairwise comparison. Also, it could be interesting performing AHP method twice, one for CAD software system selection and one for CAM software system selection with different evaluators.

5. Own approach

In this fifth chapter, the own approach of the CAD/CAM benchmark for tool making at the Styrian forging company is explained.

This own approach evaluates the five future possible scenarios, shown in Table 4, based on two different types of criteria, the black box criteria and the white box criteria.

5.1. Black box criteria

The first type of criteria are the black box criteria. These criteria are based on the idea of treating each software system like boxes whose content is unknown, therefore the resemblance with a "black box".

Each future possible scenario is evaluated objectively by its external background, and not by its intern functionalities. These criteria evaluate the number of software systems, resellers, interfaces and postprocessors needed in the scenario from three different perspectives. Hence, a general calculation could be obtained to rate the efficiency of the scenario.

Regarding the scope of the black box criteria evaluation, ANSYS 3D SpaceClaim is included but VectorCAM is not included. It is considered that VectorCAM should remain as an additional software system for the programming tasks at shopfloor.

The criteria are shortlisted in Table 11.

Table 11: Black box criteria

Black box criteria
Number of software systems
Number of software resellers
Number of interfaces
Number of postprocessors

These criteria are evaluated from different perspectives. The perspectives are shortlisted in Table 12.

Table 12: Black box criteria perspectives

Black box criteria perspectives
Current = Current situation
Additional = New item needed in this scenario
Reduced = Lesser item needed in this scenario

Regarding the number of software systems, the scenario efficiencies are estimated by adding the number of software systems needed in current situation plus the number of new software systems that are necessary to add plus the number of software systems that could be avoided. The result of this efficiency calculation is provided in "Total".

In relation to the number of software resellers, the scenario efficiencies are estimated by adding the number of software resellers needed in current situation plus the number of new software resellers that are necessary to add plus the number of software resellers that could be avoided. The result of this efficiency calculation is provided in "Total".

Concerning the number of interfaces, the scenario efficiencies are estimated by adding the number of interfaces needed in current situation plus the number of new interfaces that are necessary to add plus the number of interfaces that could be avoided. The result of this efficiency calculation is provided in “Total”.

Regarding the number of postprocessors, the scenario efficiencies are estimated by adding the number of postprocessors needed in current situation plus the number of new postprocessors that are necessary to add plus the number of postprocessors that could be avoided. The result of this efficiency calculation is provided in “Total”:

The higher the “Total”, the less efficient is the scenario.

5.2. White box criteria

The second type of criteria are the white box criteria. These criteria are based on the idea of treating each software system like boxes whose content is known and visible, therefore the resemblance with a “white box”.

In relation to the white box criteria, each future scenario is evaluated objectively in terms of the functionalities and suitability towards future digitalization processes and also subjectively including opinions of each software system that composes it.
Regarding the objective side, these criteria entail a function-based comparison to check if the scenario covers all the functionalities presented in the current software scenario, Machine Code Based Simulation criterion, Simulation of Digital Twin criterion, Tool Management Library criterion, CAM Templates criterion, Connectivity with ERP Software System criterion, Feature-Macro Mapping criterion, Application Programming Interface criterion.
Regarding the subjective side, it includes the opinion-based comparison. For this criterion a simplified version of the AHP method is implemented. This simplified version of the AHP method compares the different software tools from current software systems and alternative software systems. This comparison is based on the opinion of the Styrian forging company’s software specialists.
Regarding the mentioned future digitalization functionalities, these would improve the software landscape towards the implementation of robots, laser welding and additive manufacturing in the production process.
Regarding the scope of the white box criteria evaluation, ANSYS 3D SpaceClaim and VectorCAM are not included. It is considered that VectorCAM should remain as an additional software system for the programming tasks at shopfloor.

The white box criteria are shortlisted in Table 13.

Table 13: White box criteria

White box criteria
Function-based comparison
Machine Code Based Simulation
Simulation of Digital Twin
Tool Management Library
CAM Templates
Connectivity with ERP Software System
Feature-Macro Mapping
Application Programming Interface
Opinion-based comparison

Regarding the evaluation of the white box criteria, the scenario that satisfies the highest number of criteria would be considered as the most preferred one.

5.2.1. Function-based comparison

The function-based comparison is based on a rough comparison of the packages of the different software systems. These tools are shortlisted in CATIA V5, Work NC, EdgeCAM, Siemens NX and Esprit subchapters. More information regarding the analysed software tools is presented in the Function Comparison Table in the Appendix.

The aim of this comparison is to ensure that each software tool from the current software situation has an equivalent software tool in the alternative software systems. Hence, in the future, when purchasing an alternative software system there will not be any functionality uncovered at the CAD/CAM departments from the Styrian forging company.

Regarding CAD software systems, all the functions from CATIA V5, current CAD software system, are covered in Siemens NX, alternative CAD software system. These equivalences are mentioned in Table 14.

Table 14: CAD functions equivalences

General Name of CAD-Function	CATIA V5	Siemens NX
Assembly Design Package	Assembly Design (ASD)	NX (Advanced) Assembly
Part Design Package	Part Design (PDG)	NX for Design
Wireframe Design and Basic Surfaces Design Package	Wireframe & Surface 1 (WS1)	NX Freeform Modelling
Drafting Package	Generative Drafting 2 (GDR)	NX Drafting
Shape and Advanced Surfaces Design Package	Generative Shape Design 2 (GSD)	NX Shape Design

Regarding CAM, almost all the tools from Work NC in combination with EdgeCAM, current CAM software systems, are covered in Siemens NX and Esprit, alternative CAM software systems. These equivalences are mentioned in Table 15.

Table 15: CAM functions equivalences

General Name of CAM-Function	Work NC + EdgeCAM	Esprit	Siemens NX
Viewer Package	Viewer WNC-VW	Viewer from ESPRIT (included in Esprit Shop Floor License)	NX Viewer
Intern CAD Tool	Work NC CAD WNC-CAD EdgeCAM Part Modeler	Intern CAD from Esprit	NX for Design
Milling Package (2-Axis, 2.5-Axis, 3-Axis)	Work NC Full License WNC-FL EdgeCAM Milling	SolidMill Production Package (**) SolidMill Freeform 3-Axis	Complex Parts Machining Mold, Die & Electrode Machining Prismatic Parts Machining
High Speed Machining Package	EdgeCAM Waveform	ProfitMilling	NX Adaptive Milling
Turning Package	EdgeCAM Turning	SolidTurn Package	NX Turning
5-Axis Milling Package	Auto5 WNC-MA5 EdgeCAM Milling	SolidMill Freeform 5-Axis	5-Axis Machining
5-Axis Postprocessor & Simulation	5 Axis Post-Processor WNC-P5XCS (incudes Simulation)	Standard Postprocessor & Simulation	Postprocessing & Machining Simulation
Additional Zone Calculation	Extra Workzone Calculation Window WNC-O3XP	Non-specific package	Parallel Generate (*)
Parallel Process Calculation	Extreme Parallel Processing WNC-EPL	Parallel Processing (*)	Parallel Generate
Workflow Planning Package	EdgeCAM Intelligent Manufacturing Workflow	CheckItB4 First Step (***)	FBM Package (Feature Based Manufacturing) (*)
Feature Recognition Package	EdgeCAM Solid Machinist	Automated Feature Recognition, FX Technology	FBM Package (Feature Based Manufacturing)
Strategy Planning Package	EdgeCAM Strategy Manager	KnowledgeBase	FBM Package (Feature Based Manufacturing) (*)

(*) reseller suggests that tool exists in software, but it might not be exactly equivalent (**) possibility of SolidMill Prodution Plus for 3 rotatory axis machines in future (***) included in Knowledge Base Machining

However, it is necessary to mention that as the alternative CAD/CAM software systems, Siemens NX and Esprit, are structured in a slightly different way as CATIA V5, Work NC or EdgeCAM, it is difficult to find one exact equivalent tool for each tool of the current software systems. Usually all these equivalences with current software systems are satisfied with a combination of multiple tools in the alternative software systems.

5.2.2. Machine Code Based Simulation

This criterion evaluates whether the functionality of Machine Code Based Simulation is provided in the scenarios.

To reach certain digitalization goals in the Styrian forging company a Machine Code Based Simulation is necessary. Based on this simulation, the NC-Code, which is generated due to the postprocessing of the CAM operations, is simulated for any collisions.

5.2.3. Simulation of Digital Twin

This criterion evaluates whether the functionality of Simulation of Digital Twin is provided in the scenarios.

This exact copy of the machine provides a simulation after postprocessing as close to reality as possible.

5.2.4. Tool Management Library

This criterion evaluates whether the functionality of Tool Management Library is provided in the scenarios.

To enable a correct simulation, a digital copy of the machine, tool, work piece, raw material and clamping elements are required. In order to guarantee these in a multi-machine setting in which many people work, a Tool Management Library is necessary, which ensures that all digital tools are up to date.

5.2.5. CAM Templates

This criterion evaluates whether the functionality of CAM Templates is provided in the scenarios.

Research [23] has shown that current CAM systems offer different approaches for automation mechanisms, to assist in the creation of CAM operations. One of these CAM automation mechanisms are CAM Templates. These templates include the application of pre-fabricated CAM operations, which were previously created and tested for similar components to new geometries.

5.2.6. Connectivity with ERP Software System

This criterion evaluates whether the connectivity with ERP Software System is provided in the scenarios.

Even though the ERP software system is not included in the scope of the benchmark, certain advantages could be sought when the CAD/CAM software systems are connected to an ERP solution.

5.2.7. Feature-Macro Mapping

This criterion evaluates whether the functionality of Feature-Macro Mapping is provided in the scenarios.

Research [23] has shown that current CAM systems offer different approaches for automation mechanisms, to assist in the creation of CAM operations. One of these CAM automation mechanisms is Feature-Macro Mapping. In this mechanism, machining features with parameters such as hole diameter, pocket depth and groove-width are assigned to a specific machining sequence via macros. Every feature needs to be defined and compared with a suitable tool, which needs to be used, after to manufacture it. A challenge in this context is the clear definition of the editing features.

5.2.8. Application Programming Interface

This criterion evaluates whether the functionality of Application Programming Interface is provided in the scenarios.

Research [23] has shown that current CAM systems offer different approaches for automation mechanisms, to assist in the creation of CAM operations. One of these CAM automation mechanisms is Application Programming Interface. API extensions usually have access to the CAD model. They can do any analysis and can perform on the geometry of the CAD file. API extensions can also customize the user interface of the CAM software system and integrate with them. In addition, they are able to independently create and parameterize machining operations. However, the extensive possibilities also entail a very high level of care and, in the case of API, high licensing costs.

5.2.9. Opinion-based comparison

The opinion-based comparison relies on the subjective opinions from the Styrian forging company's employees about the comparison between current software systems' packages and alternative software systems' packages.

This comparison is not based on scientific facts, but in subjective judgement. It is crucial that the employees of the Styrian forging company are involved in the decision of the software system as they will have to use it in the future. All these opinions are analysed using the AHP method. In this own approach, the AHP method is implemented twice, one time for CAD and one time for CAM.

As mentioned in State of the Art chapter, the first step when implementing this methodology is defining the hierarchy and the elements at each level of the hierarchy. For this specific case, there are only three levels: goals, criteria and alternatives.

The goals for each AHP method are selecting the ideal CAD software system and ideal CAM software system.

The criteria for each AHP method are different. In collaboration with the Styrian forging company management, it was decided that the only criterion that would be necessary to evaluate, in this opinion-based comparison, would be software functionality. This means comparing the performance of each alternative for the different software tools from the Styrian forging company software specialists' perspective.

As the tools in CAD software systems and in CAM software systems are not the same, each AHP method contains its own criteria specific for the evaluated software.

Criteria for CAD and CAM software system selection are shortlisted in Table 16 and Table 17.

Table 16: CAD Criteria

CAD Criteria
Assembly Design Package
Part Design Package
Wireframe Design and Basic Surfaces Design Package
Drafting Package
Shape and Advanced Surfaces Design Package

Table 17: CAM Criteria

CAM Criteria
Viewer Package
Intern CAD Tool
Milling Package (2-Axis, 2.5-axis, 3-Axis)
High Speed Machining Package
Turning Package
5-axis Milling Package
5-axis Postprocessor & Simulation
Additional Zone Calculation
Parallel Process Calculation
Workflow Planning Package
Feature Recognition Package
Strategy Planning Package

At the alternative level, there are two CAD software systems and three CAM software systems.

Regarding CAD software systems, these alternatives are CATIA V5, existing at the current situation, and Siemens NX.

Regarding CAM software systems, these alternatives are Work NC plus EdgeCAM, existing at the current situation, Siemens NX and Esprit.

Once the hierarchy and the elements at each level of the hierarchy are defined, the next thing to do is the criteria weighting. For this task two questionnaires were provided to the

CAD and CAM departments. More information about the questionnaires is provided in CAD Criteria Weighting Questionnaire and CAD Criteria Weighting Questionnaire at Appendix.

In these questionnaires, the Styrian forging company's software specialists are asked to fill out pairwise comparisons between the different criteria in order to know which of those are more important towards the goal, ideal CAD or ideal CAM.

As an example, a question from the CAD criteria weighting questionnaire, to decide the preference of "Assembly Design Package" criterion over "Wireframe and Basic Surfaces Design Package" criterion, is provided in Figure 5.1.

Ist **Assembly Design Package** wichtiger als **Wireframe and Basic Surfaces Design Package**, um die geeignetste **CAD**-Software zu haben?

☐ **Nein, ebenso wichtig**

☐ **Nein, unwichtiger**

☐ **Ja, wichtiger**

Figure 5.1: Criteria weighting question

The answers from the CAD and CAM criteria weighting questionnaires are transferred to the AHP method as the following values:

Table 18: Numerical meaning of preferences

Criteria preference weight / level of importance	Definition / Answer	Explanation
1	Equally preferred (Nein, ebenso wichtig)	Both tasks are equally important towards the end goal
½ (*)	Unpreferred (Nein, unwichtiger)	The task is less critical/important towards the end goal than the other
2	Preferred (Ja, wichtiger)	The task is more critical/important towards the end goal than the other

(*) As mentioned in State of the Art chapter, when evaluating in the questionnaire, if element A is preferred to element B the numerical meaning would be 2; likewise, then element B is unpreferred to element A, resulting in a numerical meaning of ½.

Once criteria weighting is settled, the next step is to check the alternative preferences for each criterion.

In order to fulfil this task, in collaboration with the management of the company, it was decided to do one workshop with each software reseller from Siemens NX and from Esprit in two different days.

During these workshops, experts from the alternative software systems companies were asked to complete the design and the machining strategies for two common pieces of the Styrian forging company.

In the case of Siemens NX, experts from this company, were asked to complete both tasks designing and machining strategies programming. After the design workshop, the employees of design department from the Styrian forging company were asked to evaluate regarding previous criteria, as shown in Table 16: CAD Criteria, with an alternative preference questionnaire like in the criteria weighting case.

In this questionnaire pairwise comparisons, between equivalent tools from each software system, for each criterion were made. As an example, a question from this questionnaire is provided in Figure 5.2. This full questionnaire is provided at the Appendix.

3. KRITERIUM: Part Design Package

Part Design (PDG) (CATIA) ist im Vergleich zu **NX for Design (Siemens NX CAD)**…

- ☐ **Gleich gut**
- ☐ **Schlechter**
- ☐ **Besser**

Figure 5.2: Alternative preference question (CAD)

As in the previous case, during both CAM workshops, the employees of the CAM department from the Styrian forging company were asked to evaluate regarding previous criteria, as shown in Table 17, with two alternative preference questionnaires, one for each software system, like in the criteria weighting case.

In this questionnaire, pairwise comparisons, between the equivalent tools from each software system, for each criterion were made. As an example, a question from one of these questionnaires is provided in the following. Both full questionnaires are provided at the Appendix.

3. KRITERIUM: Milling Package (2-Axis, 2.5-Axis, 3-Axis)

WorkNC Full License WNC-FL & EdgeCAM Milling (WorkNC+EdgeCAM) sind im Vergleich zu **Complex Parts Machining & Mold, Die & Electrode Machining & Prismatic Parts Machining (Siemens NX CAM)**…

- ☐ **Gleich gut**
- ☐ **Schlechter**
- ☐ **Besser**

Figure 5.3: Alternative preference question (CAM)

The answers from the CAD and CAM alternative preference questionnaires are transferred to the AHP method as the following values:

Table 19: Numerical meaning of preferences

Alternative preference weight / level of preference	Definition / Answer	Explanation
1	Equally good (Gleich gut)	Both alternatives are equally good when judging just on that criterion
½ (*)	Unpreferred (Schlechter)	The alternative is worse than the other when judging just on that criterion
2	Preferred (Besser)	The alternative is better than the other when judging just on that criterion

(*) As mentioned in State of the Art chapter, when evaluating in the questionnaire, if alternative A is preferred to alternative B the numerical meaning would be 2; likewise, then alternative B is unpreferred to alternative A, resulting in a numerical meaning of ½.

6. Results

In this sixth chapter the results of the scenario decision-making procedure are presented. These results are not binding for the final decision of the Styrian forging company, nevertheless they represent a good basis for assisting the final decision-making process.

The results based on the black box criteria are presented in Results based on black box criteria.

The results based on the white box criteria are presented in Results based on white box criteria.

6.1. Results based on black box criteria

Regarding the number of software systems needed, the results are presented in Table 20.

Table 20: Comparison based on the number of software systems

Future scenario	Current	Additional	Reduced	Total
CATIA V5 → Esprit → 5-Axis Machines / 3-Axis Machines	4	1	3	**4+1-3=2**
CATIA V5 → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	4	1	3	**4+1-3=2**
Siemens NX CAD → Esprit → 5-Axis Machines / 3-Axis Machines	4	2	4	**4+2-4=2**
Siemens NX CAD → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	4	2	4	**4+2-4=2**
Siemens NX CAD → Work NC → 5-Axis Machines / 3-Axis Machines; Siemens NX CAD → EdgeCAM → 5-Axis Machines / 3-Axis Machines	4	1	1	**4+1-1=4**

In relation to the number of software resellers needed, the results are presented in Table 21.

Table 21: Comparison based on the number of software resellers

Future scenario	Current	Additional	Reduced	Total
CATIA V5 → Esprit → 5-Axis Machines / 3-Axis Machines	3	1	2(*)	**3+1-2=2**
CATIA V5 → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	3	1	2(*)	**3+1-2=2**
Siemens NX CAD → Esprit → 5-Axis Machines / 3-Axis Machines	3	1(**)	3(*)	**3+1-3=1**
Siemens NX CAD → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	3	1	3(*)	**3+1-3=1**
Siemens NX CAD → Work NC → 5-Axis Machines / 3-Axis Machines; EdgeCAM → 5-Axis Machines / 3-Axis Machines	3	1	1	**3+1-1=3**

(*) GNT Systems, VeroSoftware and Dassault Systèmes. (**) Esprit Software reseller provides also Siemens NX CAD

Regarding the number of interfaces needed, the results are presented in Table 22.

Table 22: Comparison based on the number of interfaces

Future scenario	Current	Additional	Reduced	Total
CATIA V5 → Esprit → 5-Axis Machines / 3-Axis Machines	3(*)	1	3(*)	**3+1-3=1**
CATIA V5 → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	3(*)	1	3(*)	**3+1-3=1**
Siemens NX CAD → Esprit → 5-Axis Machines / 3-Axis Machines	3(*)	1	3(*)	**3+1-3=1**
Siemens NX CAD → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	3(*)	0	3(*)	**3+0-3=0**
Siemens NX CAD → Work NC → 5-Axis Machines / 3-Axis Machines; EdgeCAM → 5-Axis Machines / 3-Axis Machines	3(*)	2(**)	2(***)	**3+2-2=3**

(*) CATIA V5 – Work NC, CATIA V5 – ANSYS 3D SpaceClaim, ANSYS 3D SpaceClaim – EdgeCAM. (**) Siemens NX CAD – Work NC, Siemens NX CAD – ANSYS 3D SpaceClaim. (***) CATIA V5 – Work NC, CATIA V5 – ANSYS 3D SpaceClaim.

Regarding the number of postprocessors needed, the results are presented in Table 23.

Table 23: Comparison based on the number of postprocessors

Future scenario	Current	Additional	Reduced	Total
CATIA V5 → Esprit → 5-Axis Machines / 3-Axis Machines	12	6	12	**12+6-12=6**
CATIA V5 → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	12	6	12	**12+6-12=6**
Siemens NX CAD → Esprit → 5-Axis Machines / 3-Axis Machines	12	6	12	**12+6-12=6**
Siemens NX CAD → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	12	6	12	**12+6-12=6**
Siemens NX CAD → Work NC → 5-Axis Machines / 3-Axis Machines; EdgeCAM → 5-Axis Machines / 3-Axis Machines	12	0	0	**12+0-0=12**

Summing up, in Table 24 , the overall calculation of the black box criteria is presented. Checking the results from black box criteria, it is likely to see that scenarios 1 to 4 are at the same level of preference, whereas Scenario 5 seems to be by far the least efficient. Hence, the combination of software systems, presented in the Scenario 5, should not be considered as a feasible solution in the final decision-making process of the Styrian forging company.

Table 24: Overall calculation of black box criteria

Future scenario	Systems	Resellers	Interfaces	Postprocessors	Total
CATIA V5 → Esprit → 5-Axis Machines / 3-Axis Machines	2	2	1	6	**11**
CATIA V5 → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	2	2	1	6	**11**
Siemens NX CAD → Esprit → 5-Axis Machines / 3-Axis Machines	2	1	1	6	**10**
Siemens NX CAD → Siemens NX CAM → 5-Axis Machines / 3-Axis Machines	2	1	0	6	**9**
Siemens NX CAD → Work NC → 5-Axis Machines / 3-Axis Machines; EdgeCAM → 5-Axis Machines / 3-Axis Machines	4	3	3	12	**22**

In order to have a clearer view of Table 24, the Figure 6.1 is presented.

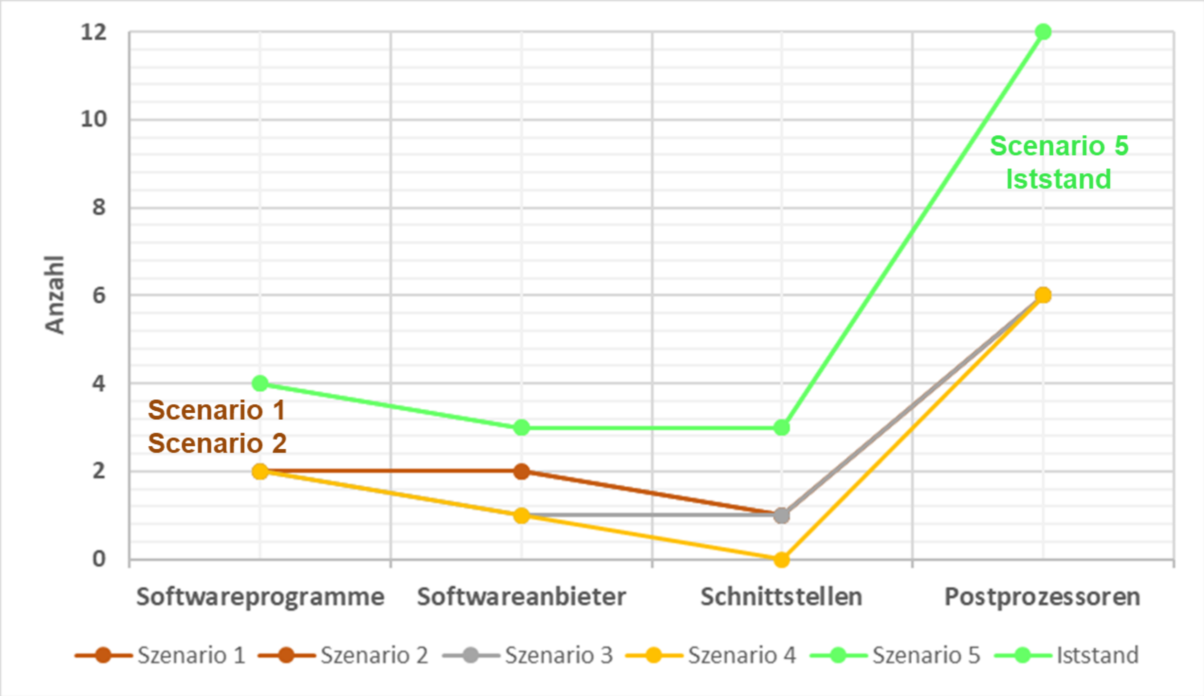


Figure 6.1: Black box criteria results

6.2. Results based on white box criteria

In Results based on white box criteria chapter, each result from the white box criteria is explained. Additionally , some suggestions and comments from Siemens NX and Esprit resellers and experts are provided.

6.2.1. Results based on function-based comparison

Regarding the function-based comparison, based on the results of this criteria, all scenarios would be feasible. All the alternative software systems have equivalent tools to those tools included in the current software system.

6.2.2. Results based on Machine Code Based Simulation

In relation to the Machine Code Based Simulation criterion, this simulation after the postprocessing would work for the scenarios 1 to 4, as they include Siemens NX CAM or Esprit in the CAM software system.

6.2.3. Results based on Simulation of Digital Twin

Regarding the Simulation of Digital Twin criterion, this functionality would work for the scenarios 1 to 4. However, the performance of Scenario 4, in this functionality, could be remarkable.

In relation to Siemens NX, the basic engine for the simulation is fully integrated in Siemens NX CAM. Reseller suggests that for the Digital Twin they only have to set up the individual milling or turning machine from the customer, that entails building up the machine kinematic model to the 3D model of the machine, defining all the limits speed of axis and other tasks.

Regarding Esprit, the reseller suggests that this functionality could be provided by an external digital twin or an internal digital twin. The internal version presents some additional advantages, as it is not necessary to import the digital copy of the tools.

6.2.4. Results based on Tool Management Library

Regarding the Tool Management Library criterion, this functionality would work for the scenarios 1 to 4. However, the performance of Scenario 4, in this functionality, could be remarkable.

In relation to Siemens NX CAM, the integrated tool library of Siemens NX CAM is just a simple library to store tools and their 3D representation. However, Siemens NX has a software called "Manufacturing Resource Library" (MRL) that provides much more functionalities such as, where the tool is stored in the real machine workshop, tool logistics and predictive maintenance.

Regarding Esprit, the reseller warns that this functionality could be provided in terms of digital copy of the tools and availability on the real machine. However, functionalities like predictive maintenance of the tools, tool logistics, ubication of the tool in the workshop are not included. These functionalities should be provided by an additional software like WinTool.

6.2.5. Results based on CAM Templates

Regarding the CAM Templates criterion, these CAM Templates would work for the scenarios 1 to 4. However, the use of CAM Templates in Scenario 4, could be value-adding.

Reseller from Siemens NX mentioned that the functionality of CAM Templates is part of Siemens NX CAM. The software systems itself provides a bunch of templates out of the box but it is also possible to customize own templates.

6.2.6. Results based on the Connectivity with ERP Software System

Regarding the Connectivity with ERP Software System criterion, the ERP could be implemented and interconnected with the CAD and CAM software systems presented in scenarios 1 to 4. However, the connectivity with an ERP solution might be more value-adding when considering a CAD/CAM complete solution like Scenario 4.

Regarding Esprit, reseller suggest that this functionality could be very beneficial as it is possible to have a current job status information.

6.2.7. Results based on Feature-Macro Mapping

Regarding the Feature-Macro Mapping, this functionality could work properly for Scenario 4 but definitely not for Scenario 1, Scenario 2 or Scenario 3. This is caused due to the data loss according to the native data transfer. As Scenario 4 is a complete CAD/CAM solution, the same data format is maintained through the whole process.

6.2.8. Results based on Application Programming Interface

Regarding the Application Programming Interface, this functionality is the most complex one. It will work properly on Scenario 4 and with restrictions on Scenario 1, Scenario 2 and Scenario 3.

6.2.9. Results based on the opinion-based comparison

These results represent the output of the AHP method. As mentioned previously in State of the Art chapter, the result is a prioritized ranking of each alternative towards the end goal in percentage values.

First, the results from the criteria weighting are presented. With these results is possible to check which functionality is more critical for CAD and CAM department.

From the Criteria Weighting Questionnaire (CAD), available in Appendix, is possible to obtain the following CAD comparison matrix (A) shown in Table 25:

Table 25: CAD comparison matrix

Kriteriengewichtung (CAD)-5 Kriterien	Assembly Design Package	Part Design Package	Wireframe and Basic Surfaces Design Package	Drafting Package	Shape and Advanced Surfaces Design Package
Assembly Design Package	1	1	1	1	1
Part Design Package	1	1	2	1	2
Wireframe and Basic Surfaces Design Package	1	1/2	1	1	1/2
Drafting Package	1	1	1	1	1
Shape and Advanced Surfaces Design Package	1	1/2	2	1	1

This previous matrix is processed with the AHP method, calculations available in Appendix, and the following CAD criteria weighting vector (W), shown in Table 26, is obtained as a result:

Table 26: CAD criteria weighting vector

Kriteriengewichtung (CAD)-5 Kriterien	Criteria Weight (W)
Assembly Design Package	19,4935%
Part Design Package	25,9870%
Wireframe and Basic Surfaces Design Package	15,1753%
Drafting Package	19,4935%
Shape and Advanced Surfaces Design Package	19,8506%

It is likely to see that “Part Design Package” is the most important CAD functionality, and the other functionalities are at the same level of importance, from Styrian forging company software specialists’ perspective.

From the Criteria Weighting Questionnaire (CAM), available in Appendix, is possible to obtain the following CAM comparison matrix (A), shown in Table 27:

Table 27: CAM comparison matrix (A)

Kriteriengewichtung (CAM)- 12 Kriterien	Viewer Package	Intern CAD Tool	Milling Package (2-Axis, 2.5-Axis, 3-Axis, 4-Axis)	High Speed Machining Package	Turning Package	5-Axis Milling Package	5-Axis Postprocessor & Simulation	Additional Zone Calculation	Parallel Process Calculation	Workflow Planning Package	Feature Recognition Package	Strategy Planning Package
Viewer Package	1,0	1,0	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Intern CAD Tool	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Milling Package (2-Axis, 2.5-Axis, 3-Axis, 4-Axis)	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
High Speed Machining Package	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0	1,0	2,0
Turning Package	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
5-Axis Milling Package	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
5-Axis Postprocessor & Simulation	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
Additional Zone Calculation	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
Parallel Process Calculation	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
Workflow Planning Package	2,0	1,0	1,0	0,5	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
Feature Recognition Package	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0
Strategy Planning Package	2,0	1,0	1,0	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	1,0

This previous matrix is processed with the AHP method, calculations available in Appendix, and the following CAM criteria weighting vector (W), shown in Table 28 , is obtained as a result:

Table 28: CAM criteria weighting vector

Kriteriengewichtung (CAM)- 12 Kriterien	Criteria Weight (W)
Viewer Package	4,666%
Intern CAD Tool	8,259%
Milling Package (2-Axis, 2.5-Axis, 3-Axis, 4-Axis)	8,638%
High Speed Machining Package	9,759%
Turning Package	9,065%
5-Axis Milling Package	9,065%
5-Axis Postprocessor & Simulation	9,065%
Additional Zone Calculation	9,065%
Parallel Process Calculation	9,065%
Workflow Planning Package	8,668%
Feature Recognition Package	9,065%
Strategy Planning Package	5,621%

It is likely to see that all CAM functionalities are approximately at the same level of importance, apart from "Viewer Package" and "Strategy Planning Package" which are slightly lower, from Styrian forging company software specialists' perspective.

Regarding the alternative preference of the CAD software systems, the needed information was provided by the Alternative Questionnaire (CAD), available in Appendix. This information was processed and the following comparison matrices for each CAD criterion were obtained, shown in Table 29, Table 30, Table 31, Table 32, Table 33, Table 34:

Table 29: Assembly design comparison matrix

Alternative Bevorzuge (CAD)- Assembly Design Package	CATIA	Siemens NX
CATIA	1	2
Siemens NX	0,5	1

Table 30: Assembly design comparison matrix

Alternative Bevorzuge (CAD)- Assembly Design Package	CATIA	Siemens NX
CATIA	1	2
Siemens NX	0,5	1

Table 31: Part design comparison matrix

Alternative Bevorzuge (CAD)-Part Design Package	CATIA	Siemens NX
CATIA	1	2
Siemens NX	0,5	1

Table 32: Wireframe design and basic surfaces design comparison matrix

Alternative Bevorzuge (CAD)-Wireframe Design and Basic Surfaces Design Package	CATIA	Siemens NX
CATIA	1	2
Siemens NX	0,5	1

Table 33: Drafting comparison matrix

Alternative Bevorzuge (CAD)-Drafting Package	CATIA	Siemens NX
CATIA	1	2
Siemens NX	0,5	1

Table 34: Shape and advanced surfaces design comparison matrix

Alternative Bevorzuge (CAD)-Shape and Advanced Surfaces Design Package	CATIA	Siemens NX
CATIA	1	2
Siemens NX	0,5	1

All these matrices were processed with the AHP method and the priority matrix made of each priority regarding each criterion was obtained, shown in Table 35:

Table 35: Priority matrix (CAD)

Alternative Bevorzuge (CAD)	CATIA	Siemens NX
Assembly Design Package	0,667	0,3333
Part Design Package	0,667	0,3333
Wireframe and Basic Surfaces Design Package	0,667	0,3333
Drafting Package	0,667	0,3333
Shape and Advanced Surfaces Design Package	0,667	0,3333

Then this matrix was transposed and multiplied with the CAD criteria weight vector (W), shown in Table 26, and the result was obtained, shown in Table 36:

Table 36: Results of suitability towards ideal CAD

Final result	Percentage of suitability towards ideal CAD
CATIA	0,667
Siemens NX	0,333

This result shows that the CATIA V5 CAD tools are more preferred than Siemens NX CAD tools, from the Styrian forging company software specialists' perspective.

However, as mentioned in State of the Art chapter, this result is based on a subjective opinion and hence cannot be fully reliable.

Regarding the alternative preference of the CAM software systems, the needed information was provided by the Alternative Questionnaire (CAM), available in Appendix. This information was processed and the following comparison matrices for each CAM criterion were obtained, shown in Table 37, Table 38, Table 39, Table 40, Table 41, Table 42, Table 43, Table 44, Table 45, Table 46, Table 47, Table 48.

Table 37: Viewer comparison matrix

Alternative Bevorzuge (CAM)-Viewer Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	1	1
Siemens NX	1	1	1
Esprit	1	1	1

Table 38: Intern CAD Tool comparison matrix

Alternative Bevorzuge (CAM)-Intern CAD Tool	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	0,5	0,5
Siemens NX	2	1	2
Esprit	2	0,5	1

Table 39: Milling (2-axis, 2.5-axis, 3-axis, 4-axis) comparison matrix

Alternative Bevorzuge (CAM)-Milling Package (2-Axis, 2.5-Axis, 3-Axis, 4-Axis)	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	1	1
Siemens NX	1	1	2
Esprit	1	0,5	1

Table 40: High Speed Machining comparison matrix

Alternative Bevorzuge (CAM)-High Speed Machining Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	1	0,5
Siemens NX	1	1	1
Esprit	2	1	1

Table 41: Turning comparison matrix

Alternative Bevorzuge (CAM)-Turning Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	0,5	1
Siemens NX	2	1	1
Esprit	1	1	1

Table 42: Milling (5-axis) comparison matrix

Alternative Bevorzuge (CAM)-5-Axis Milling Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	0,5	1
Siemens NX	2	1	2
Esprit	1	0,5	1

Table 43: 5-axis Postprocessor & Simulation comparison matrix

Alternative Bevorzuge (CAM)-5-Axis Postprocessor & Simulation	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	0,5	0,5
Siemens NX	2	1	0,5
Esprit	2	2	1

Table 44: Additional Zone Calculation comparison matrix

Alternative Bevorzuge (CAM)-Additional Zone Calculation	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	1	0,5
Siemens NX	1	1	1
Esprit	2	1	1

Table 45: Parallel Process Calculation comparison matrix

Alternative Bevorzuge (CAM)-Parallel Process Calculation	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	2	2
Siemens NX	0,5	1	1
Esprit	0,5	1	1

Table 46: Workflow Planning comparison matrix

Alternative Bevorzuge (CAM)-Workflow Planning Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	1	1
Siemens NX	1	1	1
Esprit	1	1	1

Table 47: Feature Recognition comparison matrix

Alternative Bevorzuge (CAM)-Feature Recognition Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	1	0,5
Siemens NX	1	1	1
Esprit	2	1	1

Table 48: Strategy Planning comparison matrix

Alternative Bevorzuge (CAM)-Strategy Planning Package	WorkNC+EdgeCAM	Siemens NX	Esprit
WorkNC+EdgeCAM	1	2	2
Siemens NX	0,5	1	1
Esprit	0,5	1	1

All these matrices were processed with the AHP method and the priority matrix made of each priority regarding each criterion was obtained, shown in Table 49.

Table 49: Priority matrix (CAM)

Alternative Bevorzuge (CAM)	WorkNC+EdgeCAM	Siemens NX	Esprit
Viewer Package	0,333	0,333	0,333
Intern CAD Tool	0,198	0,490	0,312
Milling Package (2-Axis, 2.5-Axis, 3-Axis, 4-Axis)	0,328	0,411	0,261
High Speed Machining Package	0,261	0,328	0,411
Turning Package	0,261	0,411	0,328
5-Axis Milling Package	0,250	0,500	0,250
5-Axis Postprocessor & Simulation	0,198	0,312	0,490
Additional Zone Calculation	0,261	0,328	0,411
Parallel Process Calculation	0,500	0,250	0,250
Workflow Planning Package	0,333	0,333	0,333
Feature Recognition Package	0,261	0,328	0,411
Strategy Planning Package	0,500	0,250	0,250

Then this matrix was transposed and multiplied with the CAM criteria weight vector (W), shown in Table 28, and the result was obtained, shown in Table 50:

Table 50: Results of suitability towards ideal CAM

Final result	Percentage of suitability towards ideal CAM
WorkNC+EdgeCAM	0,2996
Siemens NX	0,3595
Esprit	0,3410

This result shows that the Siemens NX CAM tools are more preferred than current tools from Work NC and EdgeCAM and tools from Esprit, from the Styrian forging company software specialists' perspective.

However, as mentioned in State of the Art chapter, this result is based on a subjective opinion and hence cannot be fully reliable.

Summing up, with the results shown in Table 36, the most preferred scenarios in the CAD department are Scenario 1 and Scenario 2, as they include CATIA V5 CAD software system which was the most preferred regarding CAD functionalities. With the results shown in Table 50, the most preferred scenarios in the CAM department are Scenario 2 and Scenario 4, as they include Siemens NX CAM software system, which was the most preferred regarding CAM functionalities.

7. Conclusion and Future Work

In this seventh chapter the conclusion of the CAD/CAM software system benchmark and decision-making procedure for the Styrian forging company is presented. Additionally, some suggestion of implementation (roadmap) is proposed.

For an efficient design of the CAD/CAM process chain, it is first necessary to identify the processes which implicate the biggest effort. In the particular case of the forging industry this effort relies mainly on the CAM programming tasks.

As mentioned in the previous chapters, the pressure to perform is enormous today. To stay competitive in the market, every possible advantage must be taken. In the **¡Error! No se encuentra el origen de la referencia.** subchapter and Results based on white box criteria subchapter, it was seen that the advantages of Scenario 4 in relation to scenario efficiency (black box criteria) and regarding certain digitalization functionalities (white box criteria) are clearly outstanding from the other scenarios.

Nevertheless, implementing a landscape like Scenario 4 is very complex, time consuming and expensive. It is not recommended to realize this scenario in a single iteration step, because the daily business from the Styrian forging company would suffer very much.

To avoid this problem, the first step in the implementation of Scenario 4 is the implementation of Scenario 2. As mentioned in the Results based on the opinion-based comparison subchapter, Scenario 2 would be the most preferred scenario from CAD and CAM employees perspective if just the point of view of the opinion-based comparison (AHP method) was considered. When Scenario 2 has been successfully realized, the implementation of Siemens NX CAD can be taken through and so on Scenario 4 can be reached.

The next step after implementing Scenario 4, is the installation of a Tool Management Library. It is important, that the realization of this library follows the implementation of Siemens NX CAD, otherwise no changes to the digital tools would be possible.

To enable further optimization of the NC-Code before testing on the machine, CAM simulations can be extended with a virtual CNC control. The benefit of this possibility is the perfect simulation environment and in the wider sense, the increase in efficiency in the production process.

Additionally, due to the current manual welding processes in the forging dies, this process could be improved when implementing welding robots and further additive manufacturing processes.

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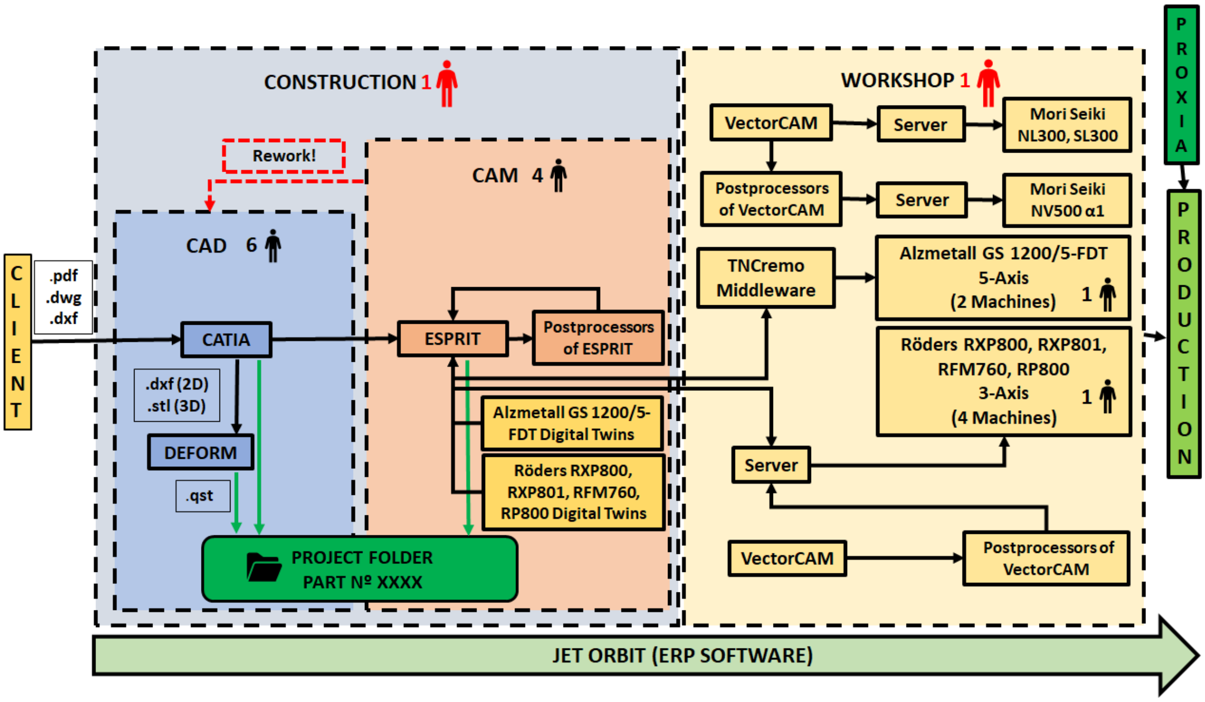
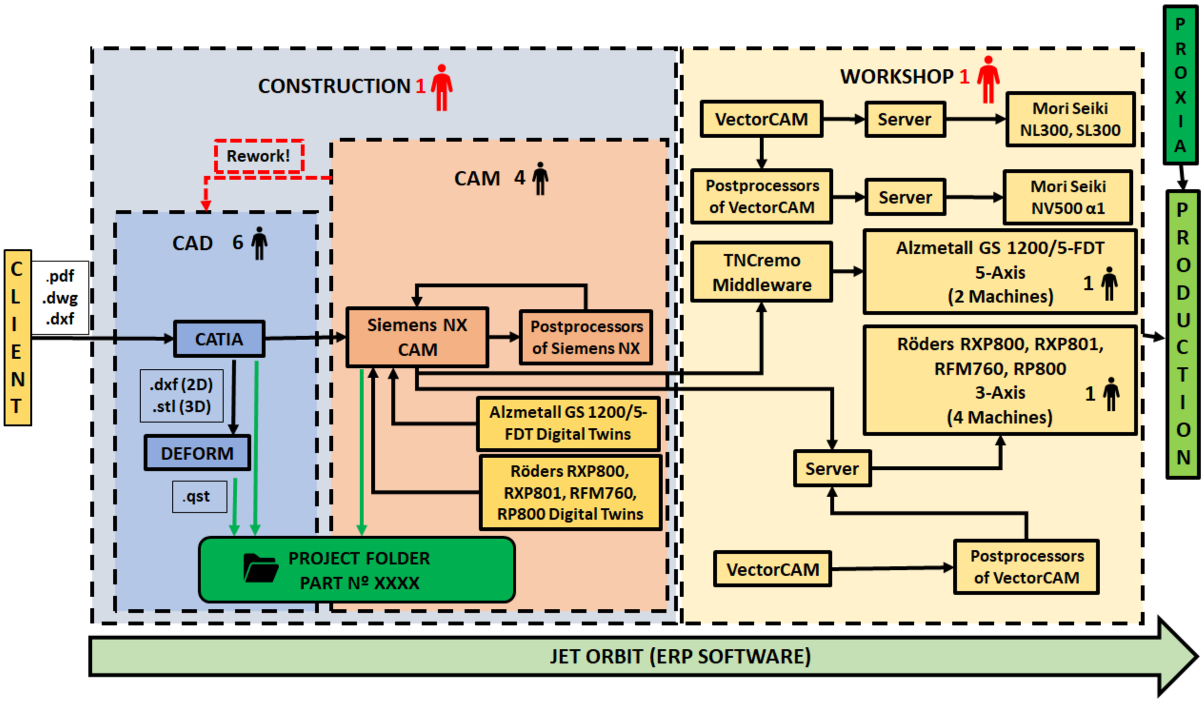
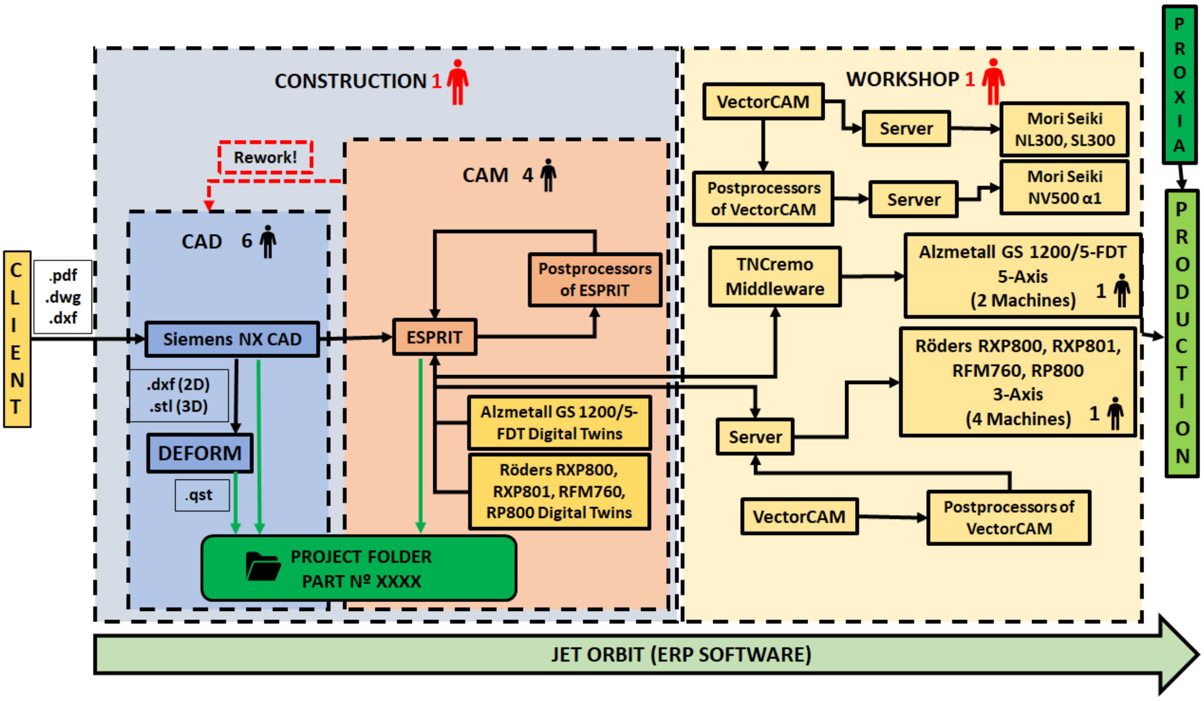
Appendix



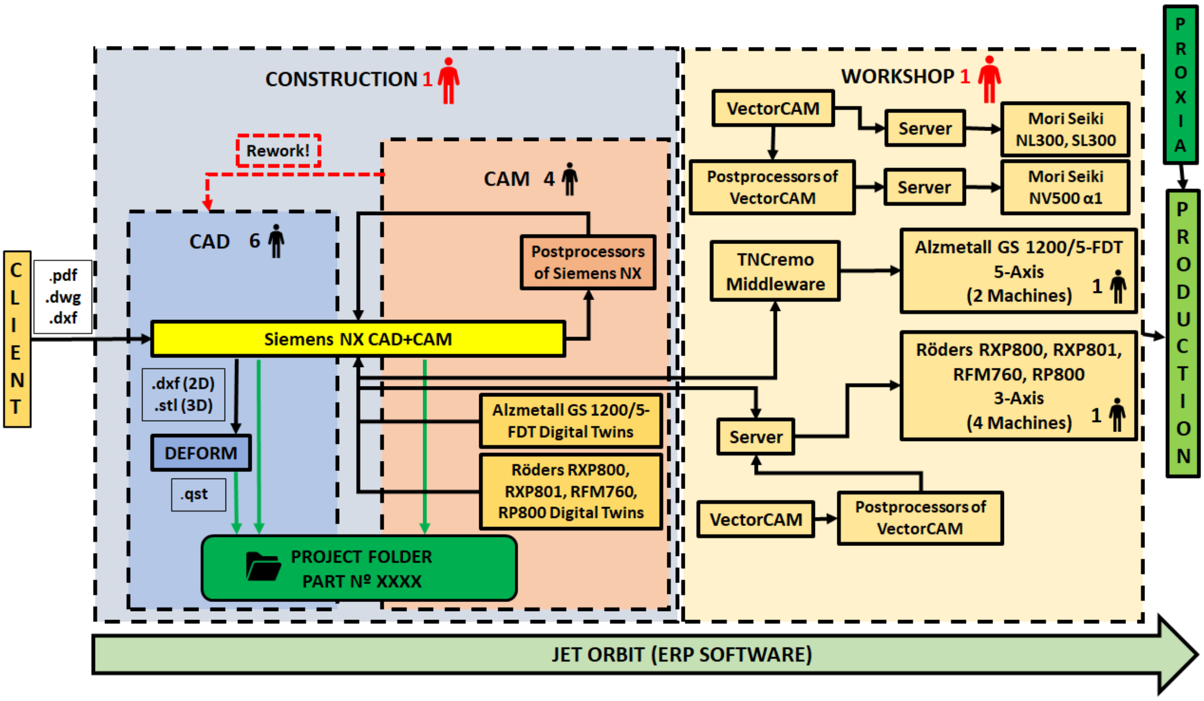
Future possible scenario I: CATIA + Esprit



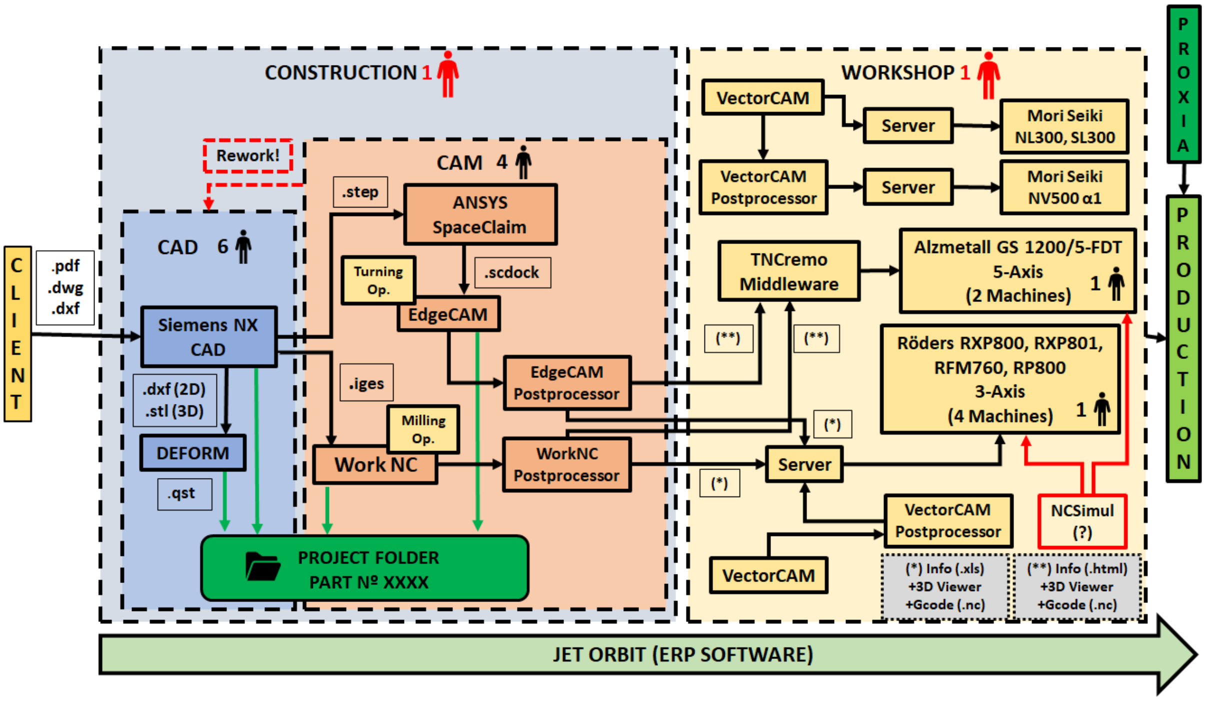
Future possible scenario II: CATIA + Siemens NX CAM



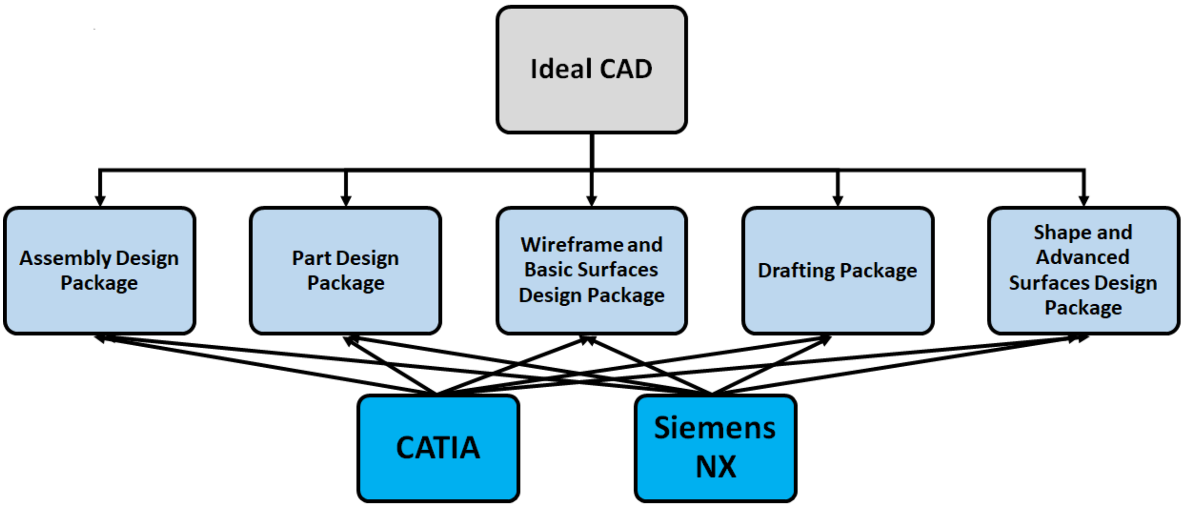
Future possible scenario III: Siemens NX CAD + Esprit



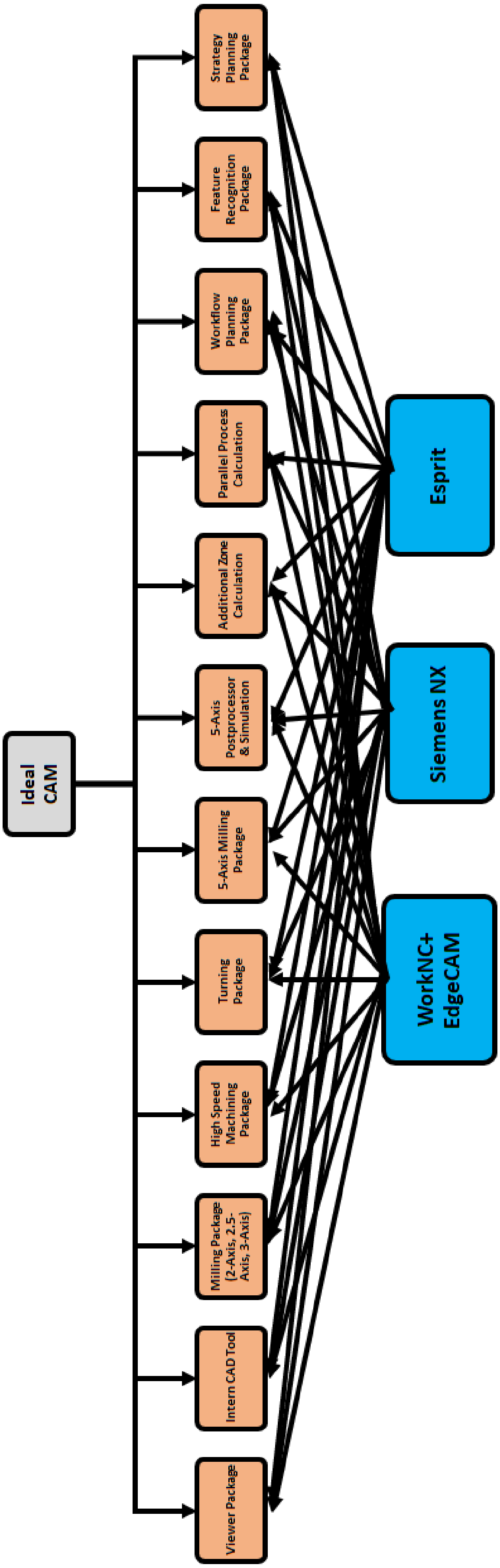
Future possible scenario IV: Siemens NX CAD + Siemens NX CAM



Future possible scenario V: Siemens NX CAD + Work NC + EdgeCAM



CAD AHP Hierarchy



CAM AHP Hierarchy

Additionally, in the Appendix Folder is possible to find:

- Function Comparison Tables ESPRIT vs WorkNC and EdgeCAM (.xls)
- Function Comparison Table Siemens NX vs CATIA, WorkNC and EdgeCAM (.xls)
- CAD Alternative Questionnaire (.pdf)
- CAD Criteria Weighting Questionnaire (.pdf)
- CAM Alternative Questionnaire Esprit (.pdf)
- CAM Alternative Questionnaire Siemens NX (.pdf)
- CAM Criteria Weighting Questionnaire (.pdf)
- Calculations of AHP Method (.xls)
- Pre-benchmark (.xls)