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UNDERGRADUATE COURSE IN CONTROL AND AUTOMATION ENGINEERING

Victor Soares Stefenon

**Development of monitoring algorithm and statistical process control methods
for quality analysis of high precision machining processes**

Aachen
2023

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for quality analysis of high precision machining processes**

Final report of the subject DAS5511 (Course Final Project) as a Concluding Dissertation of the Undergraduate Course in Control and Automation Engineering of the Federal University of Santa Catarina. Academic Advisor: Prof. João Carlos Espindola Ferreira, Dr.
Local Supervisor: Tommy Venek, M.Sc.

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Victor Soares Stefenon

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for quality analysis of high precision machining processes**

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This work is dedicated to my loving parents.

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“Science, my lad, is made up of mistakes, but they are mistakes which it is useful to make, because they lead little by little to the truth.”
(VERNE, 1864)

DISCLAIMER

Aachen, December 11th, 2023.

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ABSTRACT

High-precision machining processes are an essential part of many manufacturing industries worldwide. Due to the extremely strict quality standards for products in these industries, efficient and accurate quality analysis is a major competitive advantage. However, the process of assessing the quality of machined parts, carried out by measuring geometric deviations on their surface, is a significantly time- and financial-demanding task. In a context where hundreds or thousands of parts are machined every day, it is impractical to carry out detailed measurements and evaluations for each one of them. In order to solve this problem, this project presents the design and development of algorithms and methods for large-scale quality monitoring of machining products based on the digital twin platform for machining quality analysis from gemineers GmbH. After the development, a case study was conducted with one of gemineers' customers in order to validate the effectiveness of the algorithms and methods developed. The results of the study highlight the potential for using these resources to achieve the proposed objective.

Keywords: High-precision machining. Digital twin. Process monitoring. Statistical process control. Software development.

RESUMO

Processos de usinagem de alta precisão são parte essencial de diversas indústrias de manufatura em todo o mundo. Devido aos padrões de qualidade extremamente rigorosos dos produtos nesses setores, uma análise de qualidade eficiente e precisa é uma grande vantagem competitiva. No entanto, o processo de avaliação da qualidade de peças usinadas, realizado por meio da medição de desvios geométricos em sua superfície, é uma tarefa que demanda muito tempo e dinheiro. Em um contexto em que centenas ou milhares de peças são usinadas todos os dias, é impraticável realizar medições e avaliações detalhadas para cada uma delas. Para resolver esse problema, este projeto apresenta a concepção e o desenvolvimento de algoritmos e métodos para o monitoramento da qualidade em larga escala de produtos de usinagem com base na plataforma de gêmeos digitais para análise da qualidade de processos de usinagem da gemineers GmbH. Após o desenvolvimento, foi realizado um estudo de caso com um dos clientes da gemineers para validar a eficácia dos algoritmos e métodos desenvolvidos. Os resultados do estudo destacam o potencial de uso desses recursos para atingir o objetivo proposto.

Palavras-chave: Usinagem de alta precisão. Gêmeo digital. Monitoramento de processos. Controle estatístico de processos. Desenvolvimento de software.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMQP	Advanced Message Queuing Protocol
ASCII	American Standard Code for Information Interchange
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CNC	Computerized Numerical Control
CRISP-DM	Cross Industry Standard Process for Data Mining
Fraunhofer IPT	Fraunhofer Institute for Production Technology
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
IPW	In-Process Workpiece
KPI	Key Performance Indicator
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MVP	Minimum Viable Product
RMSE	Root Mean Squared Error
RWTH	<i>Rheinisch-Westfälische Technische Hochschule</i>
SPC	Statistical Process Control
STL	Standard Tessellation Language

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1 INTRODUCTION

This chapter aims to introduce the project described in this document. Initially, the overall context and the problem which motivated the project are presented, followed by the objectives of the project, as well as the proposed solution and achieved results. Finally, the structure of this document is presented to the reader.

1.1 MOTIVATION

With the advances of technology in manufacturing environments, many industries have evolved to very high levels of quality and precision. By consequence, these industries heavily rely on equipment that meet extremely demanding financial, quality and sustainability requirements to assure its proper operation. Because of that, high precision machining processes have become an essential part of modern industry.

An appropriate example of high precision machining is in the aerospace industry: aircraft manufacturers use a component made of blades machined into a rotor disk to form a single part [1] which achieves better aerodynamics and less space and weight in comparison to conventional rotors with individual blades [2]. These components are called blade integrated disks, or more commonly, blisks.

As seen in Figure 1, blisks have a very unique shape and rely on complex machining processes to be manufactured as a single part. Therefore, high precision machining is indispensable during their production.

Figure 1 – A compressor blisk on display at the Paris Air Show 2013.



Source: [3].

In order to meet the quality standards of machined parts, the vast majority of

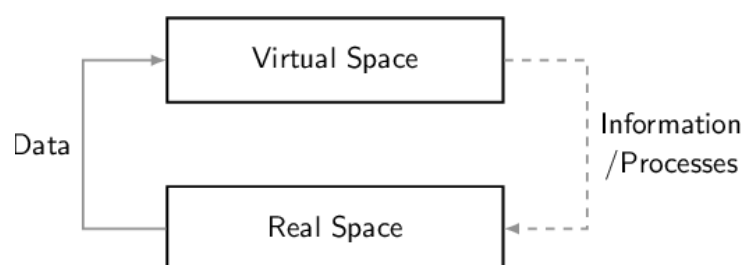
companies strongly invest in manufacturing process monitoring and quality control. According to ISO 2768, deviation tolerances can be as small as 20 μm for certain features in workpieces [4]. Therefore, measuring geometry deviations demands highly expensive and time consuming measurement processes from manufacturers.

Seeking to solve the cost and time issues in the machining process monitoring and quality control, the company gemineers GmbH was founded. Gemineers provides a software that uses data acquired from the machine (such as feedrate, spindle speed, axes loads and temperatures) to simulate the cuts performed during the process and create a digital twin of the produced part.

Digital twin, a key concept of Industry 4.0, is a virtual representation of a physical object or process capable of collecting information from the real environment to represent, validate and simulate the physical twin's present and future behavior [5]. Figure 2 illustrates the interaction between a physical system and its digital twin. Among the digital twins benefits, some of the most valuable are [6]:

- Real-time monitoring and control;
- Greater efficiency and safety;
- Predictive maintenance and scheduling;
- Scenario and risk assessment;
- Better intra- and inter-team synergy and collaborations;
- More efficient and informed decision support system;
- Personalization of products and services;
- Better documentation and communication.

Figure 2 – Schematic of the interaction between a physical system and its digital twin.



Source: [7].

The gemineers software also provides the acquired data and the manufactured workpiece deviation, making it all available in a user interface. In this way, measurements after the product is completed are no longer needed, since its quality can be thoroughly analyzed through its digital twin.

With the digital twin in hands, corporate quality teams can evaluate individual parts with high accuracy and efficiency. To determine if a product complies with quality standards, the team must analyze whether its surfaces meet the established quality requirements.

However, most products have many different parts, with different functionality. These parts, named features in the context of the project, may also differ in the geometry deviation to be considered compliant. For example, the blades of the blisk might have a much lower deviation tolerance because of their importance for the component performance compared with an inner surface of the rotor disk.

In addition, large manufacturers daily produce an expressively large number of parts: MTU, one of the global leaders in engine manufacturing, estimates to produce 6000 blisks per year [2]. For less complex parts, this number can increase significantly. In production environments such as these, it is still a significant (and frequently not feasible) effort to inspect the most critical features in each machined part, identify anomalies and find their causes.

Because of that, it is of great interest for gemineers and its clients that the software is capable of automatically evaluating each manufactured part to find non-conformities and thereby provide higher-level performance indicators, identify trends in the production and more valuable insights. It is with this opportunity to increase the gemineers software value that the project described in this document was conducted.

1.2 OBJECTIVES

The main objective of this project is to develop and validate new features in the gemineers software that provide large-scale quality monitoring to the user, enabling a much more effective detection of anomalies in machined parts and potential problems in the manufacturing process.

To achieve this, the software must be able to automatically evaluate multiple features in workpieces according to their own deviation tolerance as soon as the digital twin simulation is finished. It is also of great importance that the software evaluates the process data in these features and automatically sets tolerances for them, so that trends and anomalies in the machining process can be effectively detected.

With this in mind, the following specific objectives are set for the project:

- Develop a user interface for the selection of bounding boxes for critical features in manufactured products;
- Develop an algorithm for machining parameters and geometry deviation monitoring and calculating statistical measures of product features;

- Define Key Performance Indicator (KPI) for the quality analysis of the machined parts;
- Propose an effective method to detect anomalies and trends of machining parameters;
- Develop user interfaces for the visualization of quality control features such as charts and KPIs;
- Conduct a case study with a client of gemineers to implement and validate the features and methods proposed during the project.

1.3 DOCUMENT STRUCTURE

This document is divided into seven chapters detailing the developed project. In Chapter 2, the methodology used during the development is presented, introducing the theoretical aspects of the used frameworks and how they were applied to the project context.

In Chapter 3, gemineers, the company at which the project took place, is presented. The history and current context of the company is first introduced, followed by its business model and a detailed explanation of the features and architecture of the company's product at the beginning of the project.

Chapter 4 presents the theoretical background necessary for the reader to properly understand the development of the project. The fundamental concepts of machining processes and the related technologies are detailed, as well as the fundamentals and state-of-the-art advances of the main topics of the development, such as process monitoring and Statistical Process Control (SPC). Chapter 4 also contains an explanation of the communication protocols used in the software.

The development of the project is described in Chapter 5. The approaches tested for the product feature monitoring and SPC techniques are detailed, as well as its implementation and integration to the software. The main changes in the software user interface are also presented throughout the chapter.

In Chapter 6, the case study conducted with one of gemineers' clients is presented. Each of the study stages is detailed, alongside the analyses, results and conclusions obtained in each.

Finally, the conclusions are presented in Chapter 7. In this chapter, the finished project and the improvements achieved through it are summarized, as well as suggestions for future research and next steps in the context of the project.

2 METHODOLOGY

This chapter describes the methodology used in the project to reach the objectives stated in the previous chapter. The first draft of the features to be developed was designed by the student together with the project supervisor. This phase consisted of brainstorming possible solutions for the problems raised, from which an internal project led by the student rose.

After the project scope was created, a Minimum Viable Product (MVP) version of the algorithms was developed by the author and tested with sample data from gemineers. The output of the tests allowed improvement potentials and new required features to be listed, which were integrated to the company workflow and developed by the author. The management framework adopted for the development was Scrum, which is already consolidated in the gemineers development team.

2.1 THE SCRUM FRAMEWORK

Scrum is an iterative, incremental framework for projects and product or application development [8]. It organizes the workflow in fixed length periods called Sprints, at which increments to the product are selected from a list of improvements required for the product (called Product Backlog) and are developed to increase its value. Each sprint has a goal and includes multiple events that enable the development team to deliver value to the product, as detailed below [9]:

- **Sprint Planning:** initiates the Sprint by laying out the work to be performed for it, setting a Sprint Goal, the increment items selected for the Sprint and the plan for delivering them. This set of things is called Sprint Backlog;
- **Daily Scrum:** 15-minute events to inspect progress toward the Sprint Goal and adapt the Sprint Backlog as necessary, adjusting the upcoming planned work;
- **Sprint Review:** event to inspect the outcome of the Sprint and determine future adaptations. The Scrum Team presents the results of their work to key stakeholders and progress toward the Product Goal is discussed;
- **Sprint Retrospective:** event to plan ways to increase quality and effectiveness. The Scrum Team inspects how the last Sprint went with regards to individuals, interactions, processes and tools.

The Scrum framework and its events work based on a Scrum Team consisting of three roles [9]:

- **Developers:** the people that are committed to creating any aspect of a usable increment each Sprint;

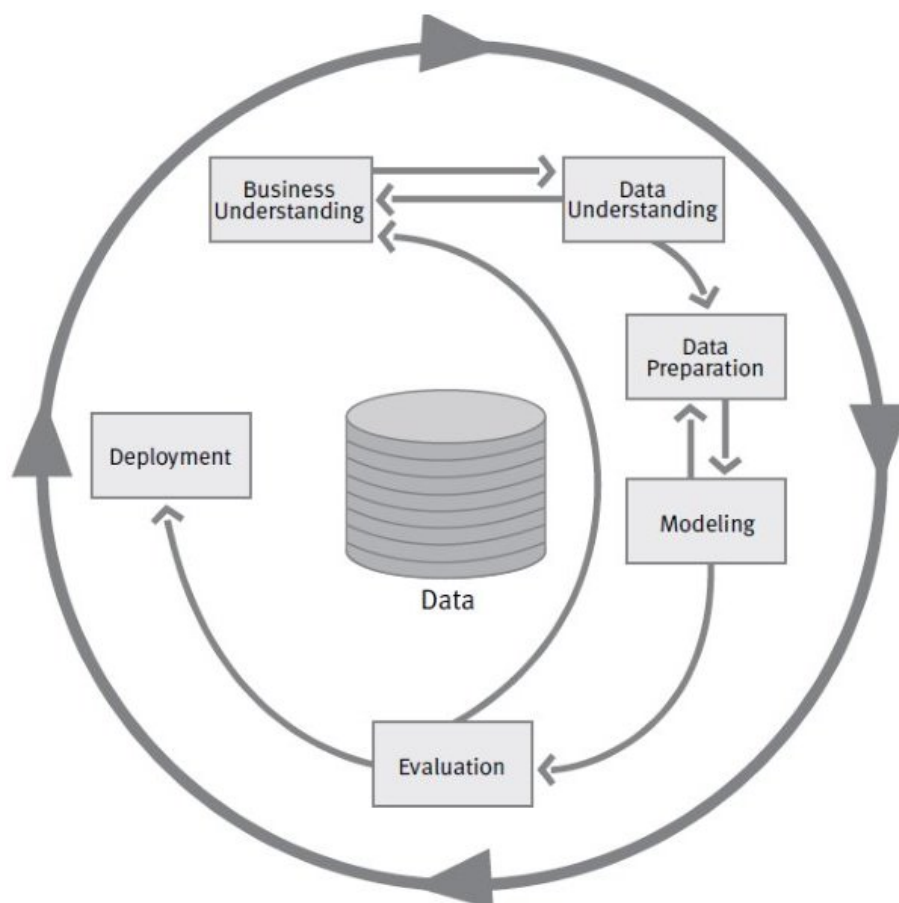
- Product Owner: person accountable for maximizing the value of the product resulting from the work of the Scrum Team, as well as effective Product Backlog management;
- Scrum Master: person accountable for properly using the Scrum framework, helping everyone understand Scrum theory and practice, as well as enabling the Scrum Team to improve its practices within it.

Due to the case study's objective of evaluating and validating statistical methods and algorithms by testing them with a customer's data set, the CRISP-DM was chosen as the reference model for the study planning and execution.

2.2 CRISP-DM

According to Shearer [10], CRISP-DM is a comprehensive data mining methodology and process model that provides a complete blueprint for conducting a data mining project. It breaks down the life cycle of a data mining project into six phases, as seen in Figure 3.

Figure 3 – CRISP-DM reference model phases.



Source: [11].

Business understanding

This phase focuses on understanding the project objectives from a business perspective, converting this knowledge into a data mining problem definition. It is an essential part of a data mining project to properly understand the business for which the solution is being developed, so that the data is correctly analyzed.

Some of the key steps of the business understanding phase are determining business objectives, assessing the situation, determining the data mining goals, and producing the project plan.

Data Understanding

The goal of the data understanding phase is to increase familiarity of the working team with the data, by identifying initial patterns and insights, assessing the quality of the data set and formulating the first hypotheses regarding it. This phase is essential to improve the decision making ability concerning the next phases, enabling more effective and quicker solutions to be found.

The steps of this phase include data collection, description, exploration and quality verification. The business and data understanding phases are strongly linked due to their common goal of gathering knowledge before working on the data. Thus, these phases are usually performed in an iterative process.

Data Preparation

The third phase of CRISP-DM consists of preparing the final data set used in the modeling phase of the project. Based on the outputs of the data understanding phase, several techniques can be applied into the data to get the the highest quality data set possible.

The main steps of the data preparation phase are the data selection, data cleaning, data construction, data integration and data formatting.

Modeling

In this phase, modeling techniques are applied to the data set prepared in the previous phase, and their parameters are tuned to fit the models to the data set. Since multiple techniques can be used to solve the same data mining problem, several models are usually selected in this phase, as well as evaluated and ranked according to their results.

The modeling phase include steps such as model selection, test designing, model creation and model assessment. Since some techniques have specific requirements on the input form, it is frequently necessary to step back to the data preparation phase while working on modeling.

Evaluation

Based on the modeling techniques implemented in the previous phase, the evaluation phase is the stage at which the project team evaluates if the model satisfies all the project requirements. As the last phase before the model deployment, it is critical to conduct it meticulously.

The key steps in this phase are the evaluation of results, the process review and the determination of next steps. To properly assess if the project requirements are met, the business understanding outputs may need to be revisited during this phase.

Deployment

The final phase of the CRISP-DM model is the deployment. In it, the knowledge gained and the model(s) developed during the project are integrated to the client's workflow to attain the project goals.

The deployment phase steps may vary according to the project requirements and the results achieved. It can consist, for example, of reports and presentations producing, delivery of algorithms applying the evaluated models or the implementation of a data mining process across the organization.

Finally, it is important to emphasize that the CRISP-DM model is not linear: starting phases must frequently be revisited during later stages of the project so that better results are achieved.

Therefore, although the classic waterfall model (approaches development in a linear and sequential manner, completing one activity before the other [12]) can still be used for high level planning, it must not be rigid in its linearity and sequentiality to avoid limiting the project progress and results.

In the case study described in this document, the modeling phase of CRISP-DM was not performed because the models developed for it were not implemented specifically in this project, but integrated into the gemineers software in general, as described in Chapter 5. Moreover, since the software was already deployed before the project, the deployment phase of the case study simply consisted of updating the software version and is therefore not detailed in this document.

3 THE COMPANY AND ITS SOFTWARE

Gemineers GmbH is a startup company in the area of software development for manufacturing analysis located in Aachen, Germany. Founded in 2021, gemineers emerged as a spin-off from the Fraunhofer Institute for Production Technology (Fraunhofer IPT), one of the leading organizations in Europe for applied research in production technology.

3.1 HISTORY

The company was born from the institute's research efforts in high precision cutting with the goal of accelerating the digitization of machining. The company logo is seen in Figure 4.

Figure 4 – Gemineers GmbH logo.



Source: Gemineers GmbH website.

The first start-up idea emerged in 2019, inspired by the large demand for a high-precision machining process quality analysis software within the manufacturing industry, as highlighted by projects conducted at the Fraunhofer IPT. In 2021, the idea received funding from the EXIST Transfer of Research, a program from the German government that supports outstanding research oriented projects that involve expensive and high-risk resource development [13].

In July 2021, the company was officially founded as gemineers GmbH. One month later, it participated in the *Rheinisch-Westfälische Technische Hochschule* (RWTH) Incubation Program, a program from the RWTH Aachen University to support founders in Europe to get their start-ups off the ground [14]. Currently, the company has partners and clients all over Europe, improving machining quality control using cutting-edge engineering technology.

3.2 BUSINESS MODEL

The gemineers business model is based on a digital twin platform for machining process quality analysis. The platform provides an end-to-end solution based on three

core elements [15]:

- **Machine and sensor data acquisition:** Plug-and-play data acquisition for all common machine controls and sensor system.
- **Fully automated digital twinning:** Automated generation of the digital twin using high-performance technology models.
- **User-friendly quality dashboard:** User-friendly evaluation of part quality in a browser-based quality dashboard.

With these elements, the software can provide relevant insights to manufacturers with lower costs and time than those required in traditional quality evaluation methods, significantly increasing the productivity and quality of industries that rely on high precision cutting processes.

Besides the platform, gemineers also provides in-depth support for its clients during software deployment, from installation in the shop floor to integration with the company network, and in production, by analyzing, evaluating and improving the data obtained through the software.

3.3 THE SOFTWARE

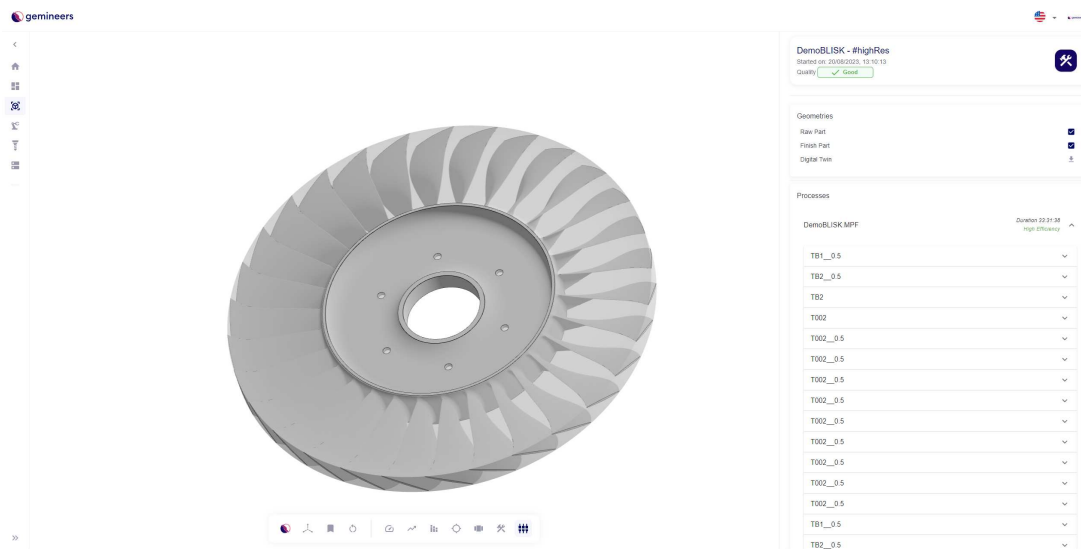
The main analyzing tool provided by the gemineers software is an interactive 3D interface which allows the user to visualize details about the machining processes. This includes the toolpath, a digital twin of the manufactured IPWs and the nominal meshes of the raw part and the final product designed in a Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM) software.

Figure 5 shows the 3D interface with the nominal meshes loaded. The slightly transparent block is the raw part, while the opaque mesh is the designed product. Similarly, Figure 6 shows the raw part mesh and the toolpath in the 3D interface, while Figure 7 shows a colorized digital twin being displayed.

The toolpath color represents the value of a process signal according to the legend in the upper left corner. The color of the digital twin, in turn, represents the geometric deviation of the IPW, according to the legend in the upper right corner of the interface. The toolpath signal selected and whether the deviation color is displayed or not are controlled through the lower toolbar buttons.

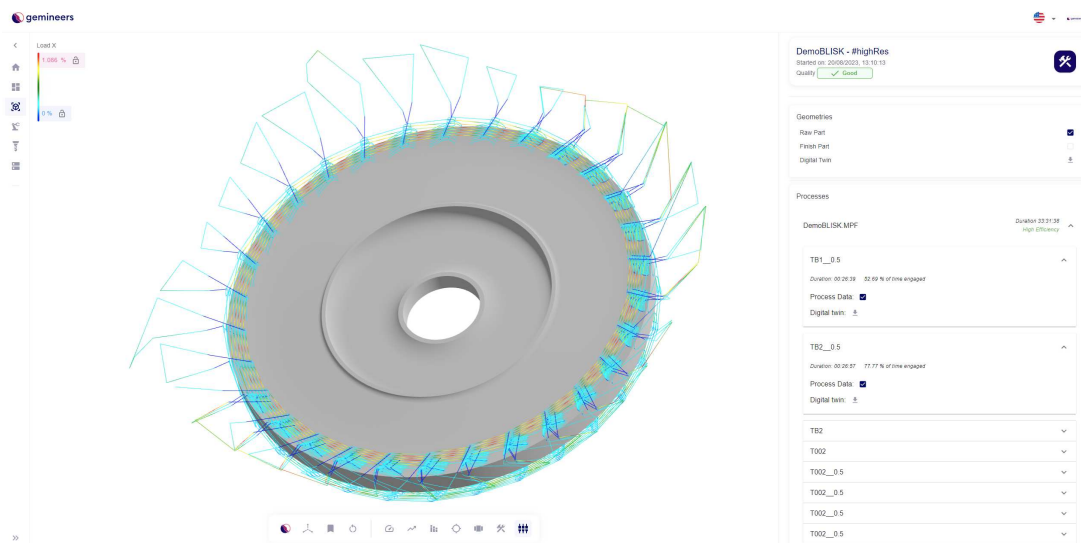
Through this interface, multiple analyses of workpiece quality can be made. Since the tool parameters and the tool position are directly related to how much deviation a manufactured part has, the user can analyze the toolpath in a specific area with higher deviation and identify potential anomalies in the behavior of the process. For instance, increased material removal usually causes higher spindle loads, which is a possible indicator of high deviation.

Figure 5 – 3D interface of the software with the raw and finish part meshes.



Source: gemineers archive.

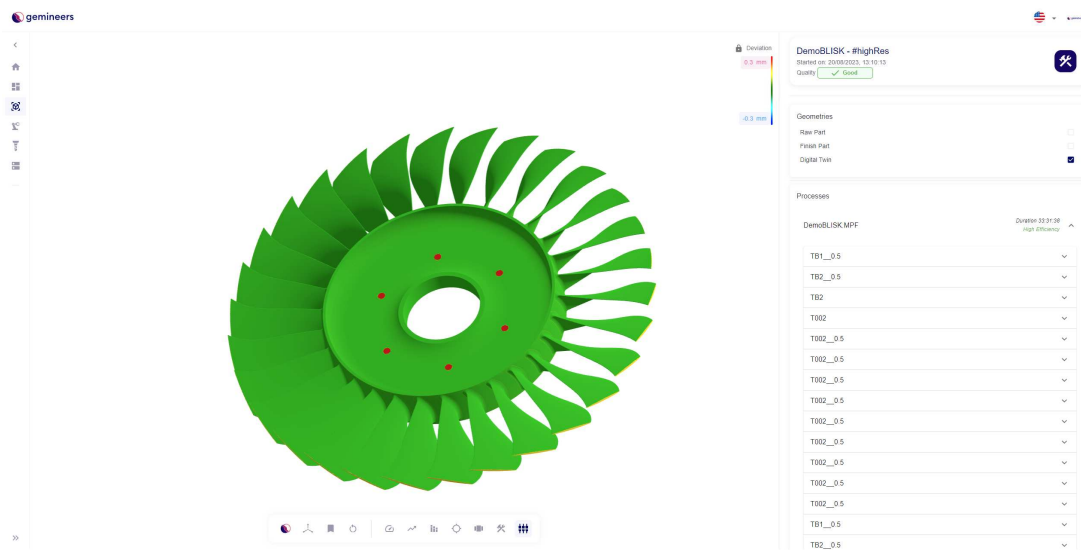
Figure 6 – 3D interface of the software with the toolpath and the raw part mesh.



Source: gemineers archive.

However, this approach lacks scalability: as stated before, it is highly impractical to analyze the quality of a serial production by evaluating each manufactured part individually. Therefore, the software still requires a specific analysis tool, which is the focus of this project.

Figure 7 – 3D interface of the software with an IPW digital twin with geometric deviation displayed.



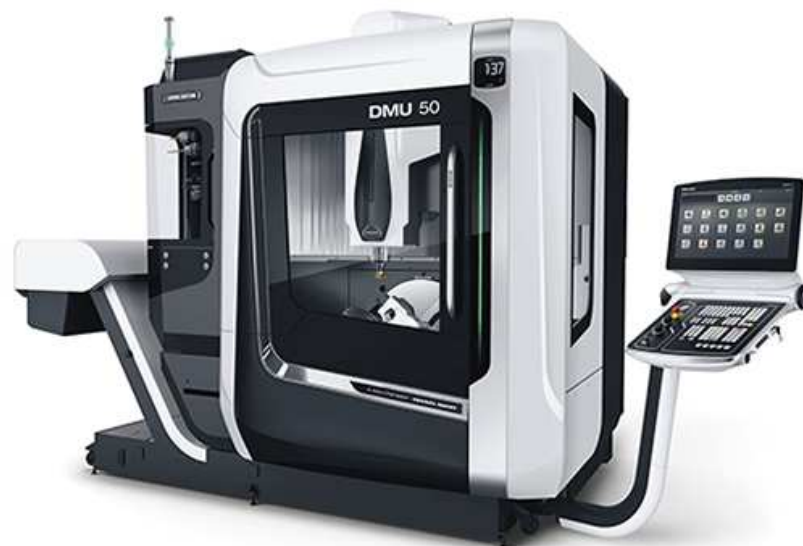
Source: gemineers archive.

4 THEORETICAL BACKGROUND

4.1 MACHINING PROCESSES

Machining processes, also known as metal cutting processes, are defined as the material removal from a workpiece in form of chips through the cutting edges of a tool [16]. Machining processes are performed with the use of machine tools, which use multiple tools to manufacture parts. An example of a modern machine tool is shown in Figure 8.

Figure 8 – DMU 50 3rd Generation machine tool.



Source: DMG MORI website.

The principle used in all machine tools is to generate the surface required by providing suitable relative motions between the cutting tool and the workpiece [17]. To achieve these motions, the machine tool can make linear or angular movements, which are performed by a component called spindle to rotate either the tool or the workpiece, depending on the machining type performed.

To do that, some parameters are of great importance:

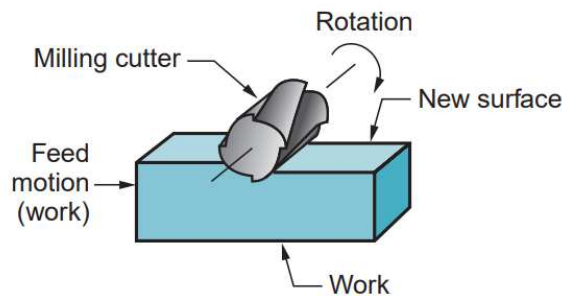
- **Feed rate:** distance by which the tool is moved per unit time. It is typically measured in mm/min;
- **Spindle speed:** number of revolutions the milling tool on the spindle makes in unit time [18]. It is typically measured in RPM or Hz;
- **Spindle load:** mechanical load in the spindle. It is typically measured in N.m or in a percentage of a nominal value;

- **Axes loads:** mechanical loads in each axis of the machine. It is typically measured in N.m or in a percentage of a nominal value.

There are three main types of machining operations:

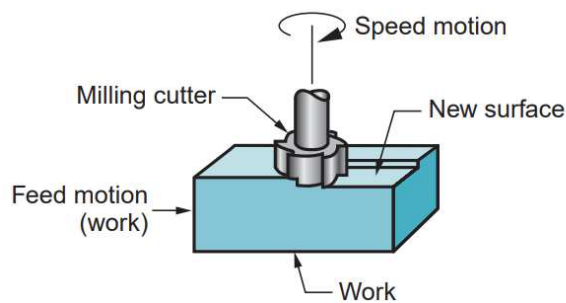
- **Milling:** the process of removing metal with rotary cutters [19]. The two basic forms of milling are peripheral milling and face milling, as illustrated in Figures 9 and 10 [20]. While milling, the tool is clamped on the spindle and the feed direction of the tool is perpendicular to the axis of rotation.
- **Drilling:** the process of rotating a cutting tool against the material with enough pressure to cause the drill to penetrate the material [21], as illustrated in Figure 11. While drilling, the tool is also clamped on the spindle but, differently from milling, the feed direction is parallel to the axis of rotation.
- **Turning:** the process of cutting a rotating part with a single-point cutting tool [22], as illustrated by Figure 12. While turning, the feed direction is parallel to the axis of rotation but, unlike milling and drilling, the workpiece is clamped on the spindle.

Figure 9 – Peripheral milling illustration.



Source: [20].

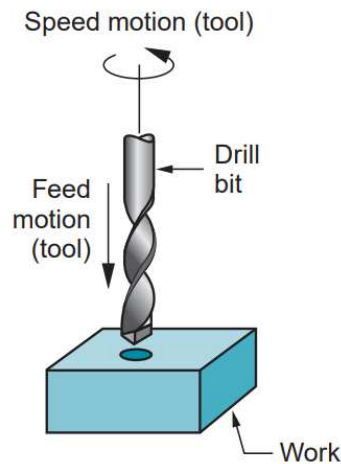
Figure 10 – Face milling illustration.



Source: [20].

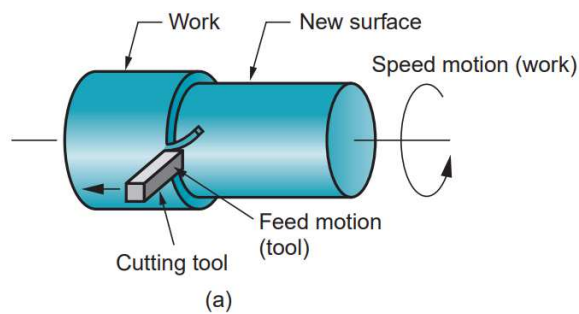
The technological advances of last decades, especially in computer science and information technology, have revolutionized machining. Since its first appearances in

Figure 11 – Drilling illustration.



Source: [20].

Figure 12 – Turning illustration.



Source: [20].

the 1950s until nowadays, Computerized Numerical Control (CNC) has become an essential part of this industry.

CNC machining consists of the use of computers to control automated machine tools, drastically reducing human interaction in the process. With this, many issues in machining are mitigated, most notably the variation caused by human interaction and the rate at which parts are produced [21].

The computers used in CNC control the machine tool by executing a program that provides the instructions required for the desired product to be manufactured. Most CNC programs are written in G-Code, a programming language developed by the MIT Servomechanisms Laboratory in the late 1950s.

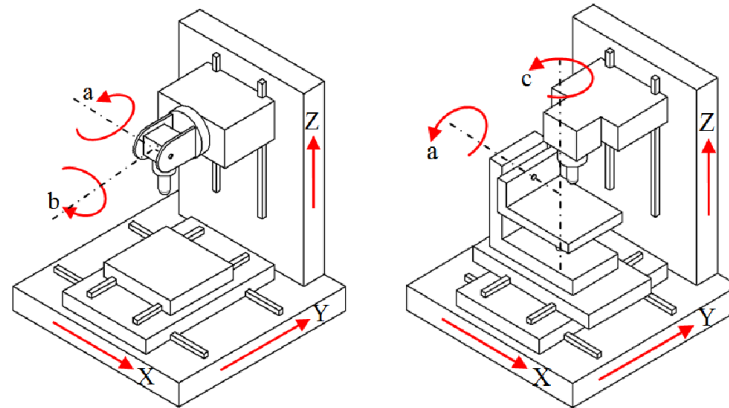
With the use of CNC, many more complex machining operations can be performed. These advances, combined with the significant reduction in engine size, led to modern-day CNC machine tools having many more degrees of freedom than older ones, being able to reach 12 translation/rotation axes.

A widely used type of CNC machine tools is the 5-axis machine tool. These machines have three translation axes, moving linearly in the x, y and z axes, and two

rotation axes, which rotate around two of the linear axes.

Figure 13 shows example configurations of the axes on 5-axis CNC machines. In the first one, the spindle can be rotated around the x and y axes (rotation axes a and b, respectively), while the table is fixed. On the other hand, in the second one, the table can be rotated around the x and z axes (rotation axes a and c, respectively), while the spindle is fixed.

Figure 13 – Example configurations of the axes on 5-axis CNC machines.



Source: [23].

4.2 COMPUTER-AIDED DESIGN/COMPUTER-AIDED MANUFACTURING (CAD/CAM)

With the advances of computation and information technology, the use of computers in the design and analysis of product conceptions has become indispensable. This concept, known as computer-aided design (CAD), enables a much more accurate and efficient design of products of varied complexity. The use of CAD software is extremely popular between engineers and designers of several industries, such as automotive industry, biomedical engineering and architectural design.

Due to the increasing use of CAD in discrete manufacturing industries, the need of higher accuracy and precision of manufacturing processes also increased drastically. Because of that, the use of software to program and control machine tools in the manufacturing of workpieces rose strongly in these industries. This concept is known as computer-aided manufacturing (CAM).

With the integration of CAD and CAM software (CAD/CAM), the end-to-end process of product conception, design and manufacturing has evolved exponentially. Nowadays, engineers can use CAD/CAM software such as Fusion 360, SOLIDWORKS and Rhinoceros 3-D to design a product and automatically generate the G-Code program that will be used by the CNC machine tool to manufacture parts of the product.

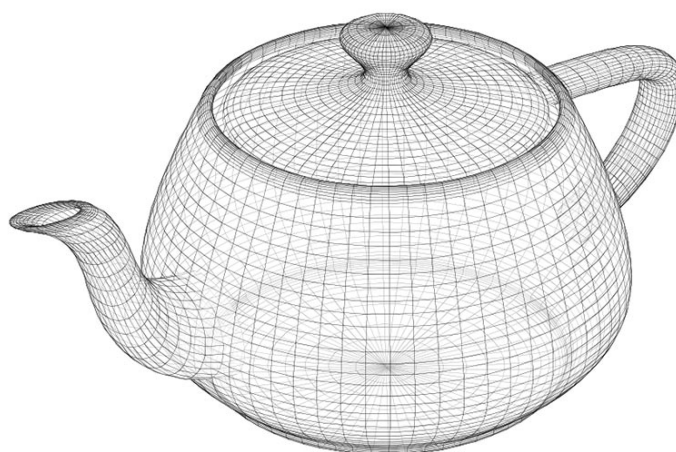
4.2.1 Geometric modeling

Geometric modeling studies methods and solutions for the mathematical description of shapes or realistic objects in computer science or computer-aided design [24]. It plays an important role in CAD/CAM software, as it is the technique used for creating digital representations of three-dimensional real objects. For this reason, this topic is extensively studied to find ways to increase the accuracy and efficiency of the representations.

There are three main types of geometric modeling:

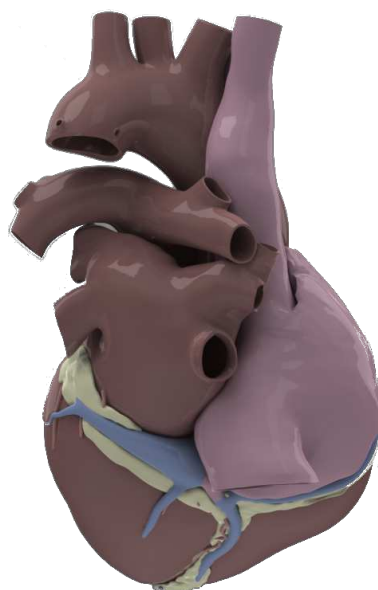
- **Wireframe modeling:** 3-D line drawing of an object showing only the edges without any side surface in between [25], as seen in Figure 14. In general, it is the simplest and most efficient way of modeling 3-D objects. However, the lack of detail between the edges and hard visualization are frequently major disadvantages of wireframes;
- **Solid modeling:** representation of the complete 3-D object, representing the surface and the solid mass between them [25], as seen in Figure 15. Despite being the most accurate type of geometric modeling, it is highly complex to describe solid masses mathematically and is very expensive in terms of computing power;
- **Surface modeling:** representation of the 3-D object as a set of faces, as seen in Figure 16. It consists of a wireframe with the gaps between edges filled following a certain method. It is a middle ground between wireframe and solid modeling, containing more information than wireframes while being simpler and easier to compute than solids.

Figure 14 – Wireframe model of teapot.



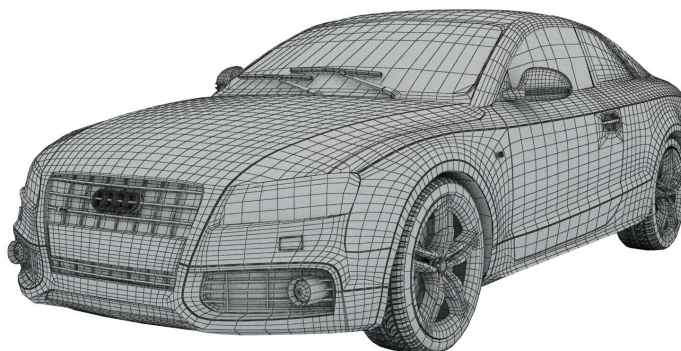
Source: [26].

Figure 15 – Solid model of human heart.



Source: [27].

Figure 16 – Polygon surface modeling of car.



Source: [28].

In CAD/CAM applications, the surface is in general the most important part of the product, since machining processes should not affect the inner part of the solid. Therefore, surface modeling is frequently the most viable option for the design and analysis of products in CAD/CAM software.

Standard Tessellation Language (STL) file format

STL (acronym for Standard Tessellation Language) is a file format used to describe three-dimensional surfaces. The STL format was created in 1987 by 3D Systems,

a 3-D printer manufacturer, as part of their stereolithography printing technology for commercial 3-D printers [29].

The goal of an STL file is to describe a 3-D object through multiple triangles, which represent this object when connected together. A higher number of triangles leads to a higher resolution and, therefore, the possibility to faithfully represent more complex designs.

Although higher resolutions allow the development of higher-quality 3-D models, the size of an STL file can become extremely large if the resolution is too high, leading to more difficult rendering and storage. Therefore, it is important to balance the quality of the representation with its usability.

The format of STL files can be either American Standard Code for Information Interchange (ASCII) or binary. Both formats generally store the same information, but in different ways. AN STL file consists of a header with metadata (such as filename, author and date) and a sequence of triangle descriptions. The triangles in STL are described by four three-dimensional vectors: one for each of the triangle vertices and one normal vector. In ASCII format, a triangle is represented as visible in Code Snippet 1.

```
1 facet normal  $n_x$   $n_y$   $n_z$ 
2     outer loop
3         vertex  $v_{1x}$   $v_{1y}$   $v_{1z}$ 
4         vertex  $v_{2x}$   $v_{2y}$   $v_{2z}$ 
5         vertex  $v_{3x}$   $v_{3y}$   $v_{3z}$ 
6     endloop
7 endfacet
```

Code Snippet 1 – Representation of a triangle in STL files in ASCII format.

As seen in the structure, the file gives a raw description of the triangle with no information on their connection. Because of that, the software used to visualize an STL file must be able to create a single object with the triangles described in it.

STL files do not have support for color information by standard. However, since the color of a 3-D object can represent important information in many situations, there are various non-standard variations on the STL file format for adding color information. Usually, this information is added as a new set of bits in each triangle indicating the RGB value of its color.

The simplicity of STL files, alongside the possibility of representing very complex shapes by expanding the resolution of the object as much as possible while staying within the available computing power, makes it an extremely popular file format in additive manufacturing and CAD applications.

4.3 STATISTICAL PROCESS CONTROL

4.3.1 Concept

SPC is defined as the use of statistical techniques to control a process or production method [30]. These techniques provide insights on unexpected behavior on a process, helping to identify anomalies and trends in it.

The first important consideration to the SPC theory is that every process has variations, which can be due to random variations in the input of the process, such as atmospheric pressure and humidity fluctuations. These causes are known as common causes. If all the variations of a process are explained by common causes, the process is considered in statistical control.

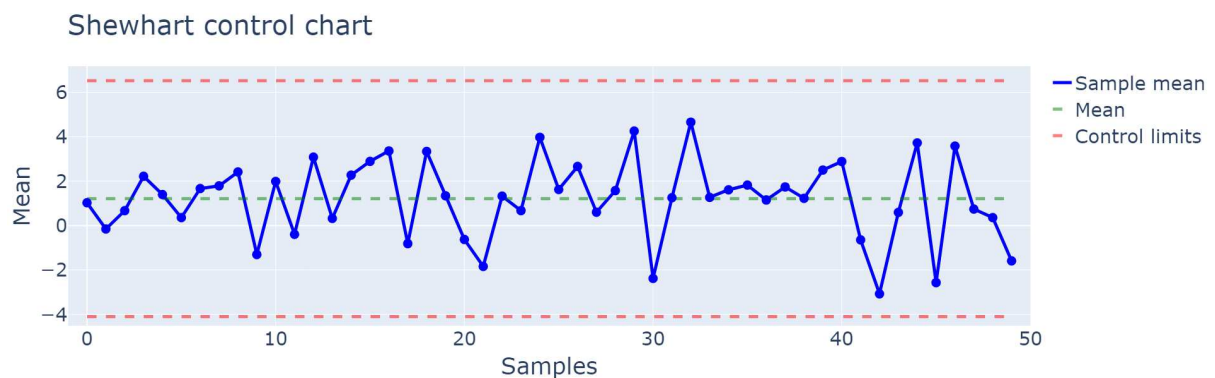
However, variations of larger magnitude are usually consequence of factors which are not inherent to the process and represent a change of its state. If the variation of a process is explained by these causes, known as special causes, the process is considered out of statistical control, or simply out of control.

An out-of-control process can be in this state because of a worsening or improvement in it. Nonetheless, in both cases it is still considered out-of-control, because both of them indicate that the process has variations which are not only due to common causes.

4.3.2 Control charts

The most important resource of SPC is the control chart. Proposed by Walter Shewhart in the book *Economic Control of Quality of Manufactured Product* [31], the control chart contains timely ordered samples of the evaluated process, a mean horizontal line and two control limits horizontal lines, which are used as a guide to identify out-of-control-samples. Figure 17 shows an example of a Shewhart control chart.

Figure 17 – Example of Shewhart control chart.



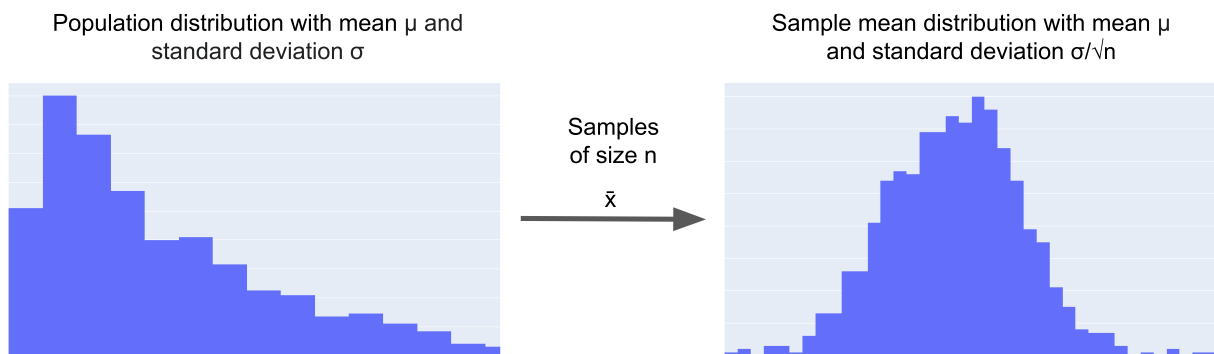
Source: [28].

The identification method proposed by Shewhart is based on the Central Limit Theorem, which states that if samples of size n are drawn from a population with a

mean μ and a standard deviation σ , then as n increases in size, the distribution of sample means approaches a normal distribution with a mean μ and a standard error of the means of σ/\sqrt{n} [32].

This means that, no matter how the data of a process are distributed, the distribution of the means of samples of this process will approach a normal distribution if a large enough number of samples is acquired. Figure 18 illustrates the Central Limit Theorem.

Figure 18 – The Central Limit Theorem.



Source: author (based on [32]).

In the normal distribution, approximately 99.72 % of the data is within the range $\bar{x} \pm 3\sigma/\sqrt{n}$. Therefore, any point over $\bar{x} + 3\sigma/\sqrt{n}$ or below $\bar{x} - 3\sigma/\sqrt{n}$ strongly suggests that the process is out of control. For this reason, the Shewhart control limits are traditionally set as $\bar{x} \pm 3\sigma/\sqrt{n}$.

Over the years, control charts were widely adopted in industry, becoming an essential tool for quality control. Consequently, various improvements and extensions were proposed for the method introduced by Shewhart. The next sections focus on two of the most popular and adopted methods.

4.3.3 Western Electric rules

The Western Electric rules are four rules published by the Western Electric Company [33]. Based on the Shewhart charts, this method expands the control limits by creating three zones in the chart:

- **Zone A:** Between 2σ from the centerline and the control limit (3σ);
- **Zone B:** Between 1σ and 2σ from the centerline;
- **Zone C:** Within 1σ from the centerline.

Based on these zones, four rules are then established:

- **Rule 1:** A single point falls outside the 3σ limit (beyond zone A);

- **Rule 2:** Two out of three successive points fall in Zone A or beyond;
- **Rule 3:** Four out of five successive points fall in Zone B or beyond;
- **Rule 4:** Eight successive points fall in Zone C or beyond.

4.3.4 Nelson rules

The Nelson rules were published by Lloyd S. Nelson in a 1984 article [34]. In it, Nelson proposed eight rules:

- **Rule 1:** One point beyond Zone A;
- **Rule 2:** Nine points in a row in Zone C or beyond;
- **Rule 3:** Six points in a row steadily increasing or decreasing;
- **Rule 4:** Fourteen points in a row alternating up and down;
- **Rule 5:** Two out of three points in a row in Zone A or beyond;
- **Rule 6:** Four out of five points in a row in Zone B or beyond;
- **Rule 7:** Fifteen points in a row in Zone C (above and below centerline);
- **Rule 8:** Eight points in a row on both sides of centerline with none in Zones C.

It is important to note that the extensions of the control charts presented allow more unexpected patterns to be identified, but at the same time significantly increase the sensitivity of the method. Thus, it is important to critically evaluate which tests are suitable for the controlled process.

4.4 COMMUNICATION PROTOCOLS

A communication protocol is a set of formal rules describing how to transmit or exchange data, especially across a network [35]. Due to the widespread use of protocols in information technology systems with a wide variety of objectives, several communication protocols have their use standardised.

For the data processing area of the gemineers software, which is covered by the project, two communication protocols are essential and extensively used: Hypertext Transfer Protocol (HTTP) and Advanced Message Queuing Protocol (AMQP).

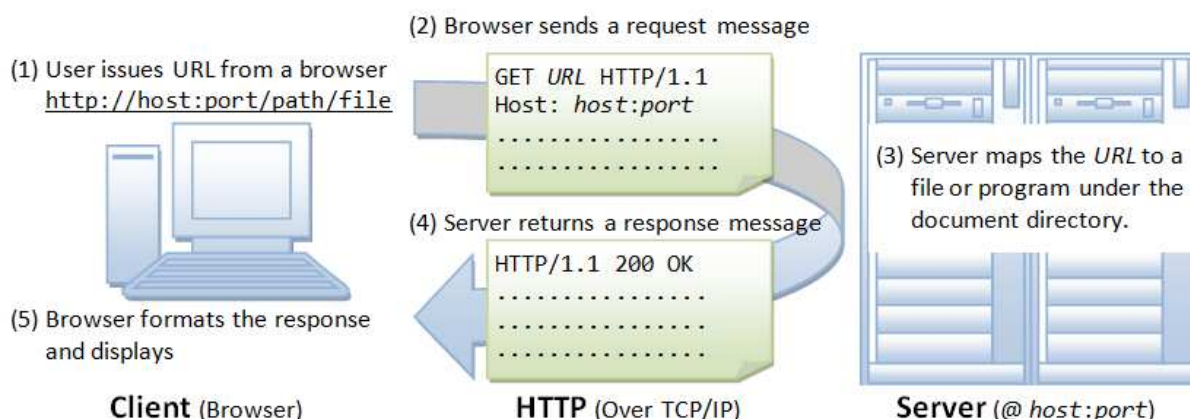
4.4.1 Hypertext Transfer Protocol (HTTP)

HTTP is a stateless application-level protocol for distributed, collaborative, hyper-text information systems [36]. It is the most used protocol in the world wide web, being mainly used for exchanging hypermedia documents such as text, images, audios, etc. between web browsers and servers. It follows the client-server model: a client makes a request, which is processed by the server, that returns a response for the client.

HTTP defines a set of request methods to indicate the action to be performed for a given resource [37]. Some of these methods can send a message body with hypermedia documents, such as POST and PUT. On the other hand, an HTTP response contains the resource returned by the server according to the action indicated by the request. The response returns a status code indicating if a request has been successful and, if required, a body containing hypermedia documents.

Both requests and responses also contain headers, which describe the request resources and the behavior of the server or the client, such as authentication tokens and content type. The process of an HTTP GET request is illustrated in Figure 19.

Figure 19 – Schematic of the process of an HTTP GET request.



Source: [36].

4.4.2 Advanced Message Queuing Protocol (AMQP)

AMQP is an open standard for passing messages between applications or organizations. It connects systems, feeds business processes with the information they need and reliably transmits onward the instructions that achieve their goals [38].

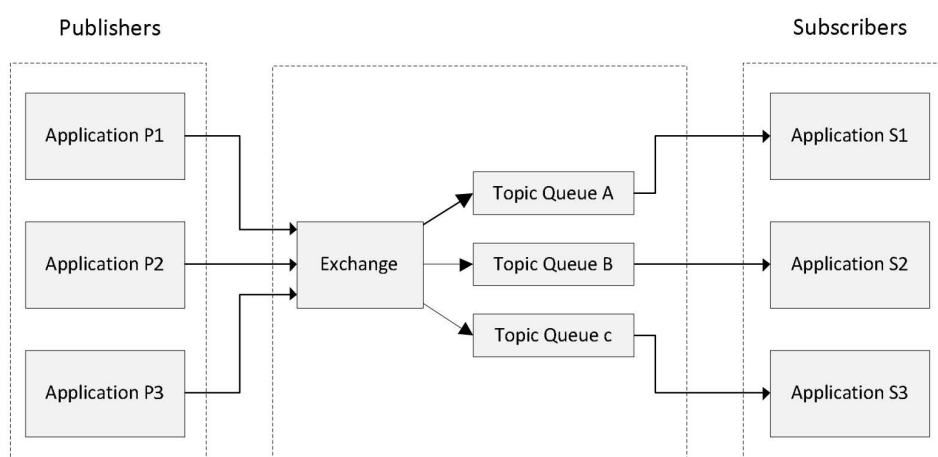
Due to its ability to connect applications from different organizations and developed in different technologies, AMQP is widely used in various business cases, such as connecting business partners, communication in financial services and Internet of Things (IoT) applications. Among these cases, it is important to highlight its use in distributed systems, which is gemineers' use case, where messages are used to trigger

data processing microservices and provide the necessary information for them to run correctly.

AMQP has multiple specification versions. This section focuses on version 0-9-1, which is used on the gemineers software. According to the AMQP protocol specification [39], an advanced message queuing server accepts messages, routes them to different consumers depending on arbitrary criteria and buffers them in memory or on disk when consumers are not able to accept them fast enough.

This model divides these tasks into two distinct roles: (1) the exchange, which accepts messages from producers and routes them to message queues; and (2) the message queue, which stores messages and forwards them to consumer applications. Typically, the exchange decides how to route a message through a routing key, which is a virtual address published with the message. Figure 20 shows the AMQP communication architecture.

Figure 20 – AMQP communication architecture.



Source: [40].

5 SYSTEM DEVELOPMENT

This chapter presents the development stage of the project described in this document. It details all the features, methodologies and techniques tested and developed by the author.

5.1 PRODUCT FEATURE MONITORING ALGORITHM

When machined products are designed, many quality requirements are established. Since machining processes always have imperfections, the most common requirement concerns the deviation for the manufactured part. However, it is also very common for products to have certain surfaces where high precision is of much greater importance, as the example in section 1.1.

In order to solve this issue and the lack of higher level quality indicators in the gemineers software, an algorithm called Product Feature Monitoring was developed. It is responsible for evaluating specific spots of an IPW limited by bounding geometries (called features), calculating stats and setting a status indicator for the workpiece based on the tolerances assigned. C++ was chosen as the programming language for the service due to its support for manipulating geometry meshes and processing data with high performance.

The algorithm was implemented in the software architecture as a new microservice, integrated with the data processing pipeline and communicating with the other services.

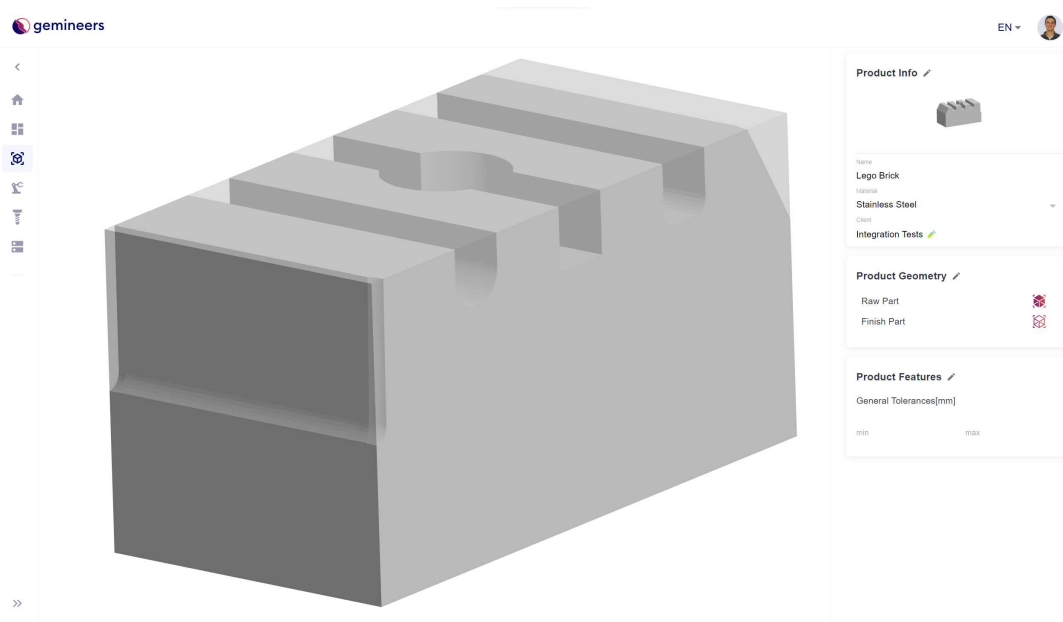
5.1.1 Feature Creation

Before the development of the service itself, it was necessary to provide an interface for the user at which the product features could be created. Using the 3D interface as basis, a page for product creation was added to the web application. In this page, the user can upload meshes from the CAD/CAM designs of the product in STL format, which will then be displayed in the interface. Figure 21 shows a use case of the product creation page for the "Lego Brick", an example product used for testing purposes at gemineers.

With the meshes uploaded, the user can add features to the product, which are divided in groups for organization purposes. When a feature geometry type is selected, the user can select the spot of the feature in the product.

After creating a feature, the user can add variables to be monitored. Since the most important quality factor of a machined part is how similar it is to the designed product, the most important (and most common) variable monitored in a feature is the geometric deviation. However, as made clear in section 3.3, machine tool parameters

Figure 21 – Product creation page.



Source: gemineers archive.

are directly responsible for ensuring that the workpiece is compliant to quality standards. Thus, it is also very important to monitor one or more of these signals in the product features.

Because of that, the user can choose to monitor the geometric deviation and the process signals, such as spindle load, feed rate and axes temperature, in the feature. Since deviation tolerances are usually defined during product design, this value can be manually added by the user to the feature, setting a minimum and maximum tolerated value.

On the other hand, defining tolerances for process signals can be much more challenging, since various factors may influence them. For this reason, the user must not set them manually, and one of the following stages of the project consisted of evaluating anomaly and trend detection methods for process signals.

After confirming the product and feature creation, the product is uploaded to the database and is available in the user interface and for the data processing services.

5.1.2 Data Processing

With the user interface ready for the creation of products and their features, a new microservice called Product Feature Monitoring was developed to monitor them. Since tolerances can be specified for both geometric deviation and for process signals, the computation performed by the service can be divided in two stages: the process signals monitoring and the deviation monitoring.

After identifying the process signals and deviation data of interest for each feature, statistical measures are calculated for each of them, such as mean, median, mode,

standard deviation and quantiles. A feature quality KPI was also defined based on the deviation of each feature.

5.2 STATISTICAL PROCESS CONTROL IMPLEMENTATION

With the statistical measures calculated by the process signals monitoring, it is possible to use SPC methods to identify trends and anomalies in the machining parameters at each product feature. The first part of this section is reserved for detailing the methods chosen for the solution, while the second section presents the integration of the methods to the software.

5.2.1 Anomaly and trend detection methods

The control charts algorithms were developed in Python due to the language's high prototyping potential and support for data handling and visualization libraries. The developed function supports the evaluation according to three sets of criteria, which are detailed below. If one or more data points fit a criterion, they are highlighted in red in the control chart. When a criterion based on a sequence of points is satisfied, all points in the sequence are highlighted so that the detected pattern is more easily recognized.

The first set is focused on the detection of outlier samples based on the normal distribution, consisting of the 3σ criterion originally proposed by Shewhart and a criterion proposed by Oakland [32].

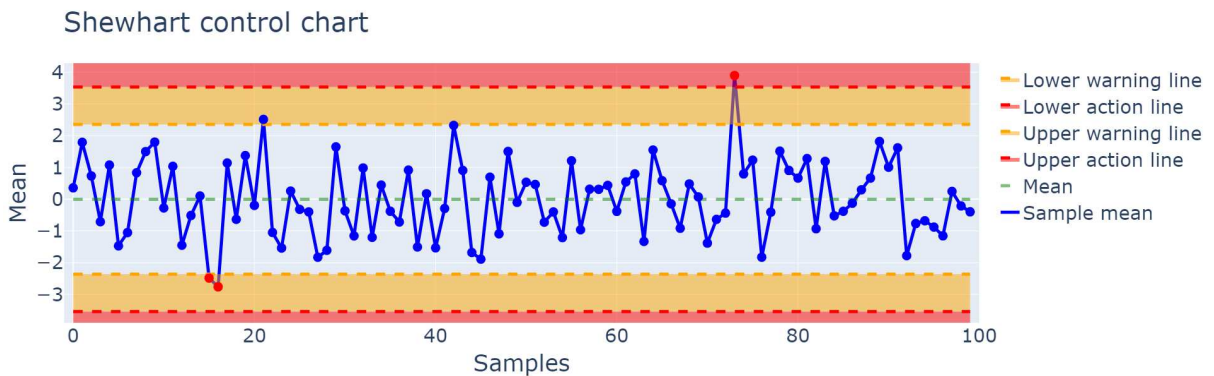
In a normal distribution, 95.44% of the data are within the range $\bar{x} \pm 2\sigma$, which means the chance of two consecutive points lying outside this range is approximately $0.456 \cdot 0.456 = 0.2\%$. Therefore, two consecutive points below the lower warning limit or above the upper warning limit suggest that the process is out of control, similarly to the 3σ case.

Firstly, the average \bar{x} and standard deviation σ of the sample means are calculated. Afterwards, the action and warning lines are calculated, as described in section 4.3. Finally, the function automatically checks if any sample fits in one of the out of control conditions.

Figure 22 shows an example generated using the function *normal* from the *random* submodule from *NumPy*, a Python library that provides a multidimensional array object, as well as derived objects and an assortment of routines for fast operations on arrays [41]. This function generates n samples from a normal distribution parameterized by the informed mean and standard deviation. In the example, the function returns an array of 100 values of a normal distribution with mean 0 and standard deviation 1.

As seen in Figure 22, point 74 is above the Upper Action Line and is therefore considered an out of control sample. Furthermore, points 16 and 17 are below the Lower Warning Line. Since these points are consecutive, they are considered out of

Figure 22 – Example of control charts for the outlier detection criteria.



Source: author.

control samples. On the other hand, point 22 is over the Upper Warning Line, but since the points before and after it are not, it is not considered an out of control sample.

The second set of criteria consists of the Western Electric rules. For that, a third line is added to the plot, given by $\bar{x} + \sigma$, thus creating the three zones designed for this approach. The algorithm then verifies if any data sample fits in the four rules to highlight them in the control chart.

Figure 23 shows three plots where each of them has samples satisfying one of the Western Electric rules. The first rule was omitted because it is identical to the action line rule from the first approach and is already visible in Figure 22.

Finally, the last set of criteria consists of the Nelson rules. Since this approach uses the same zones proposed by Western Electric, but modifying one and adding three new rules, the same lines were used for the plot. The verification for the five new rules is performed alongside the already existing three.

Figure 24 shows five plots where each of them has samples satisfying one of the Nelson rules. The three rules identical to the Western Electric's have been omitted as they are already visible in Figure 23.

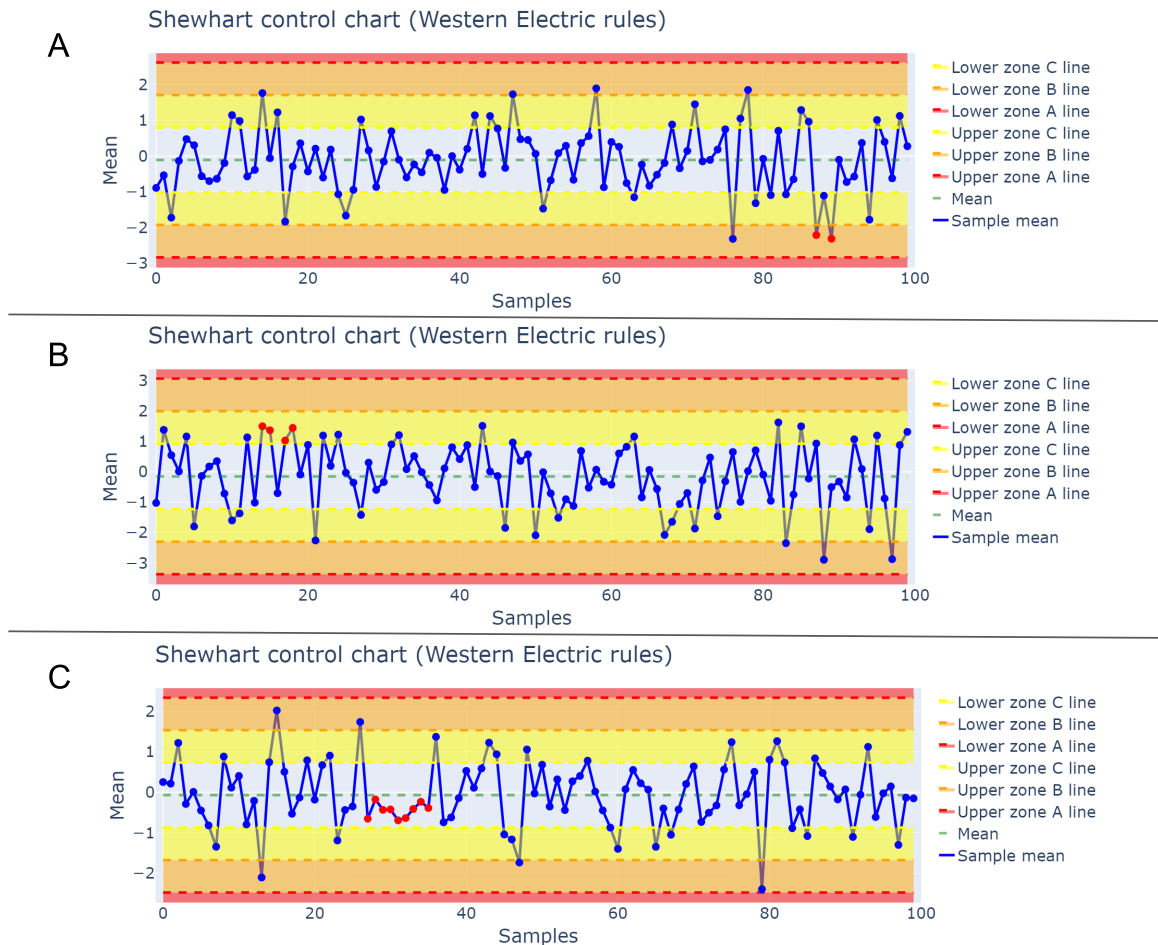
The algorithms used to evaluate and plot the control charts are shown in section A.1 of Appendix A.

5.3 KPI VISUALIZATION

With the statistical measures and quality KPIs computed, it is necessary to make these data available for the user. The quality indicators are displayed in the user interface alongside the manufactured parts. Figure 25 shows the products page the Lego Brick with the quality KPIs displayed.

The three possible statuses for the KPI are distinguished by the red, yellow and green colors, resembling a traffic light. Whenever the status is different from "Good", the "Review" label is displayed. If the user inspects a part under review and concludes it is compliant, the indicator can be updated from "Review" to "Reviewed" to indicate

Figure 23 – Example of control charts for the Western Electric rules (a) 2, (b) 3 and (c) 4.



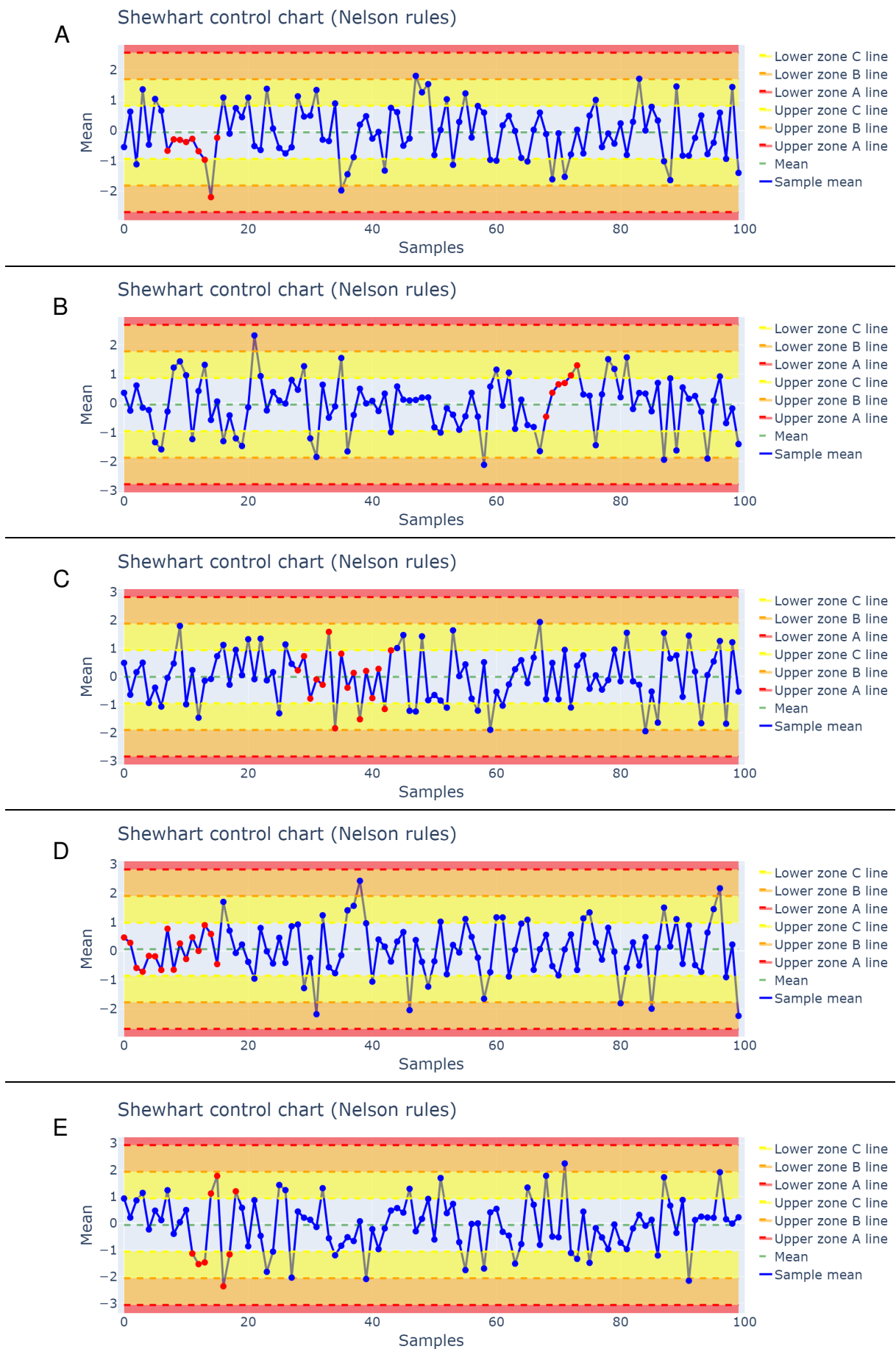
Source: author.

that, as two of the parts in Figure 25. Through these indicators, the user can quickly acknowledge the quality of each manufactured workpiece.

To assess the overall quality of a manufacturing process, the user can access the control charts previously presented in the user interface as well, as visible in Figure 26. The charts are available for each product feature and can be accessed through the products page, in the feature group tab. One chart is generated for each signal monitored in the feature.

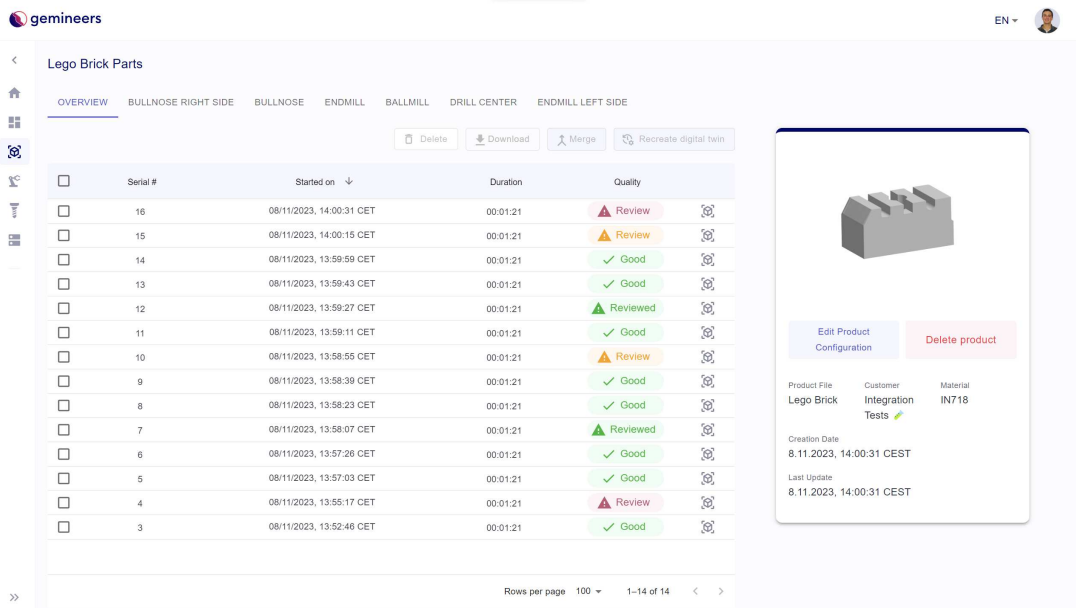
When hovering a data point, the user can visualize detailed information about it, such as the part serial number, its creation date and key statistical measures. If the user clicks on the point, the interface is redirected to the 3D visualizer with the process data and digital twin of the selected operation (Figure 27).

Figure 24 – Example of control charts for the Nelson rules (a) 2, (b) 3, (c) 4, (d) 7 and (e) 8.



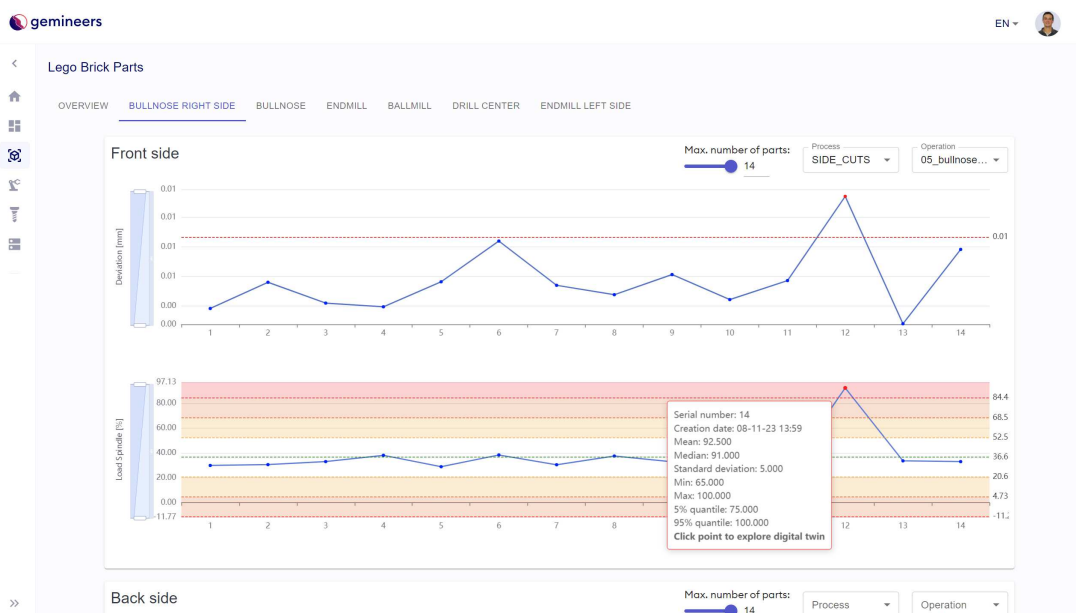
Source: author.

Figure 25 – Product details page with quality indicators for each part.



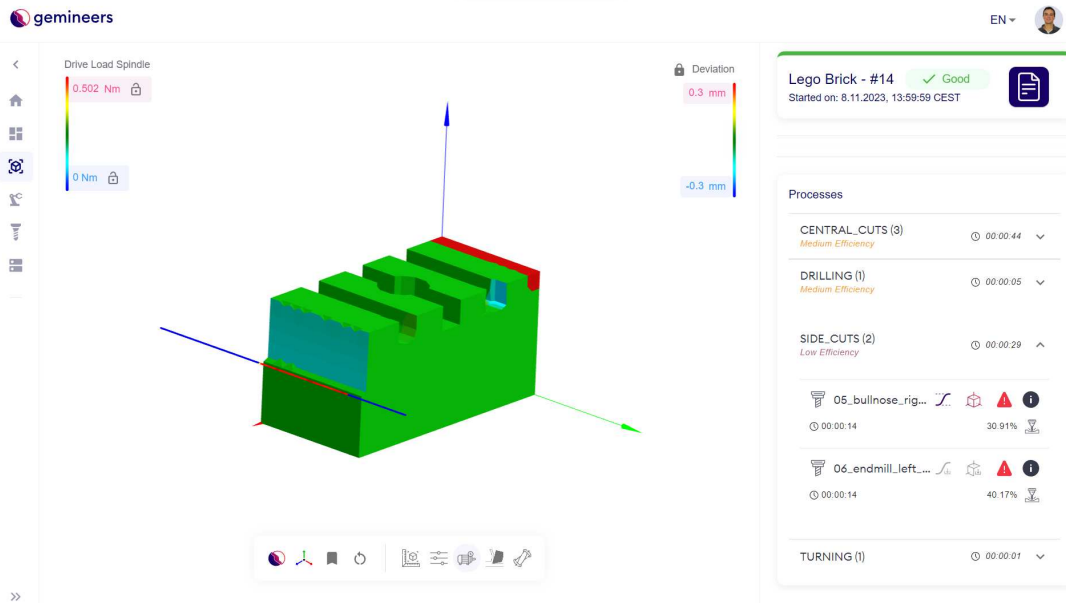
Source: gemineers archive.

Figure 26 – Product details page with quality indicators for each part.



Source: gemineers archive.

Figure 27 – Redirected page after selection of sample in control charts.



Source: gemineers archive.

6 CASE STUDY

After the development of the feature monitoring and quality evaluation algorithms and their integration to the software, validating the proposed implementations was a necessary stage of the project. To do that, a case study was performed in one of gemineers' clients, a key stakeholder in the developed features. The next sections detail each stage of the case study.

6.1 BUSINESS UNDERSTANDING

The case study was performed in a gemineers client from the aerospace industry. The company is one of the global leaders in aircraft engine supply for civil and military aircraft. Due to non-disclosure agreements, the company name and sensitive information are omitted from this document.

The client in question purchased the gemineers software to monitor a production line of low-pressure turbine disks. Modern aircraft engines, especially jet engines, are designed with low-pressure and high-pressure compressors and turbines to maximize their operation efficiency.

The low-pressure compressor is responsible for precompression, while the high-pressure compressor handles main compression [42]. The low-pressure and high-pressure turbines, on the other hand, are the components that drive the low-pressure and high-pressure compressors, respectively.

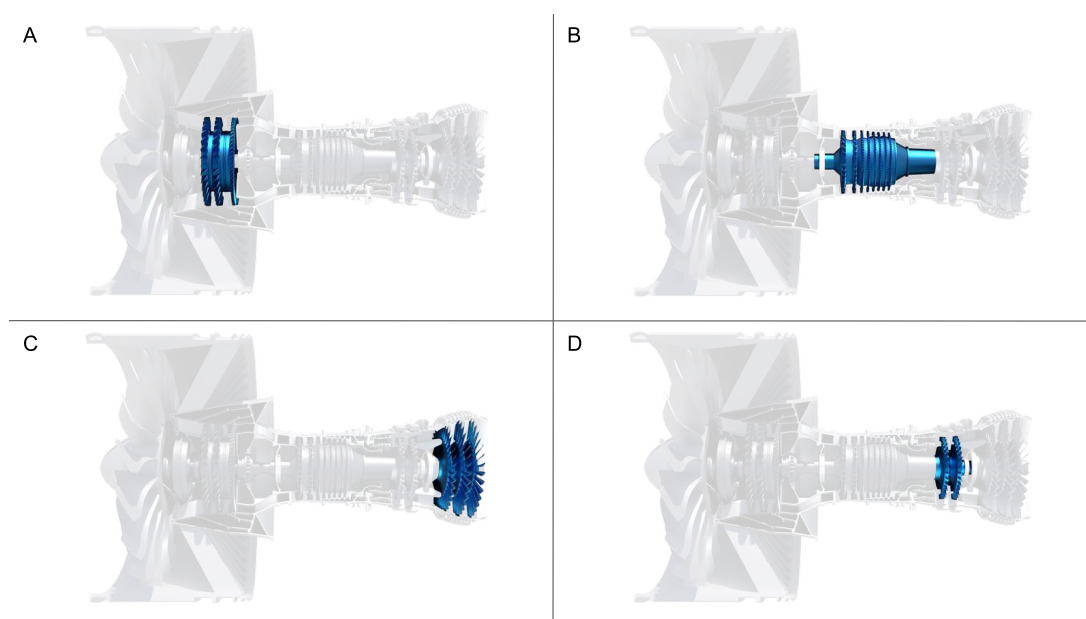
By using this multi-stage design, the compression and expansion of air and fuel in the engine are significantly improved, leading to more efficient combustion and overall performance. Figure 28 shows the design of a jet engine with the compressors and turbines highlighted.

One of the key components of turbines is the rotor disk, as the example shown in Figure 29. The disks are responsible for holding the turbine blades and rotate at high speeds, being subjected to massive temperatures and centrifugal forces. For this reason, manufactured disks must meet highly demanding quality standards.

The product's quality requirements are established by the company's engineers in the design phase. They set multiple critical areas (referred to as "balloons"), which represent specific features of the product, and defined deviation tolerances for each of them, ranging from 25 to 100 μm . Figure 30 shows an example of possible balloons named "1" and "2" in the workpiece cross section drawing. The drawing, balloon and measurements were modified by the author due to non-disclosure agreements.

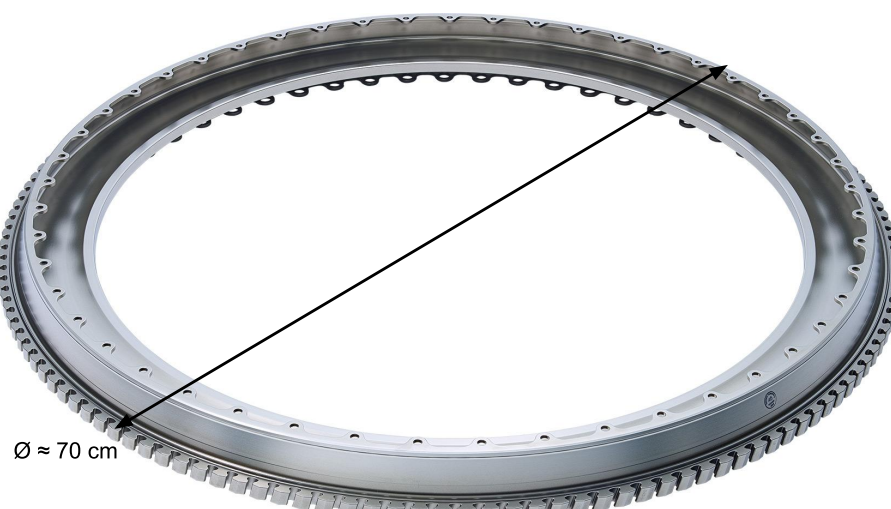
At the start of the project, the company measured the deviation at the balloons by using touch probes as the one shown in Figure 31. This component is connected to the machine tool, which positions its tip in the desired surface point to precisely measure the coordinates at which the surface is touched. With these data, the deviation at the

Figure 28 – Jet engine design highlighting the (a) low-pressure compressor, (b) high-pressure compressor, (c) low-pressure turbine and (d) high-pressure turbine.



Source: [43].

Figure 29 – Example of low-pressure turbine disk.



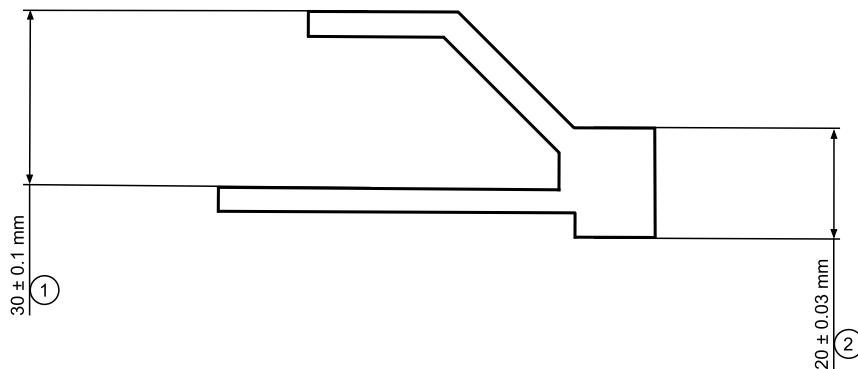
Source: [44].

balloons is calculated and uploaded to the company database.

This procedure provides high accuracy and precision to the quality control of the manufactured workpieces. However, it requires the machine tool to stop machining several times to perform touch probe measurements, which can significantly reduce the productivity of the manufacturing line. Moreover, certain balloons are positioned in regions of the surface which the touch probe cannot reach. Therefore, measurements must be manually performed after the workpiece is finished as well.

These two factors are the main improvements the client sought with the gemi-

Figure 30 – Product cross section drawing with examples of critical balloons monitored by the case study client.



Source: author.

Figure 31 – Touch probe measuring a workpiece.



Source: [45].

neers software. By adding features for each critical balloon in the product, the software is capable of monitoring the geometry deviation and process signals in them and generating statistics and quality indicators for the product.

The turbine disk manufacturing consists of five processes which were carried out in four machine tools of the company shop floor. With the exception of the round holes, cut through drilling operations, all product features were machined by turning operations, which are the main focus of the client's quality analyses. A process is always completely performed in the same machine tool, but different processes of a workpiece might be carried out in different machine tools.

The goal of the project was to generate accurate digital twins for the manufactured disks, monitor the critical balloons of the product through them and obtain statistics and quality evaluation that enables the detection of nonconformities in the produced workpieces and the manufacturing line.

To achieve that, key milestones of the project can be summarized as follows:

- Perform the machining simulations using the machine tool data to generate the disks' digital twins;
- Apply the feature monitoring algorithm to obtain data for each critical balloon;
- Evaluate the workpiece and machining process quality using the feature monitoring algorithm output;
- Validate the results by comparing them to the touch probe measurements.

6.2 DATA UNDERSTANDING

The client purchased two licenses of the gemineers software to acquire data from two of the four machine tools in the shop floor.

The main issue concerning the data was that, since the data of only two machine tools were acquired, many workpieces had missing data from certain processes. Figures 32 and 33 respectively display the number of workpieces with data of each process and the number of workpieces by number of processes with data. This was a significant obstacle on generating digital twins of the final stage of the workpiece because the cuts performed by some operations were not simulated due to lack of data.

Figure 32 – Bar chart of number of workpieces by process.

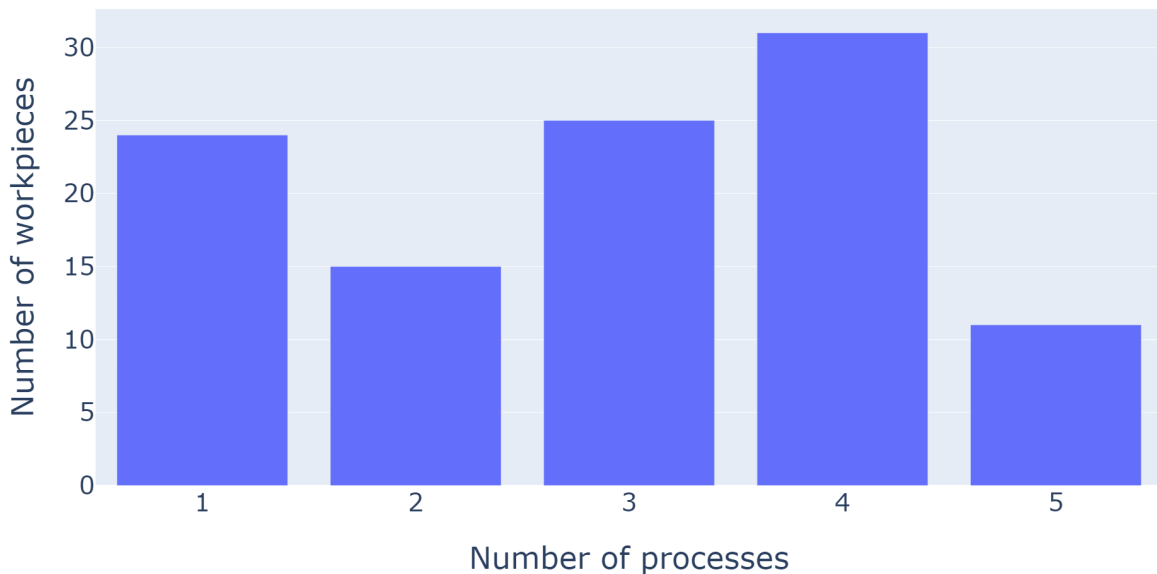


Source: author.

In the turning operations, the tool moved in the y and z axes directions, but was always in the point $x = 0$. This behaviour is explained by the fact that the workpiece

Figure 33 – Bar chart of number of workpieces by number of processes.

Number of workpieces by number of processes



Source: author.

rotated around the z axis in order to machine the symmetrical features of the product. For the same reason, the spindle load of the processes was acquired as the load of axis c, i.e. the rotation axis around z.

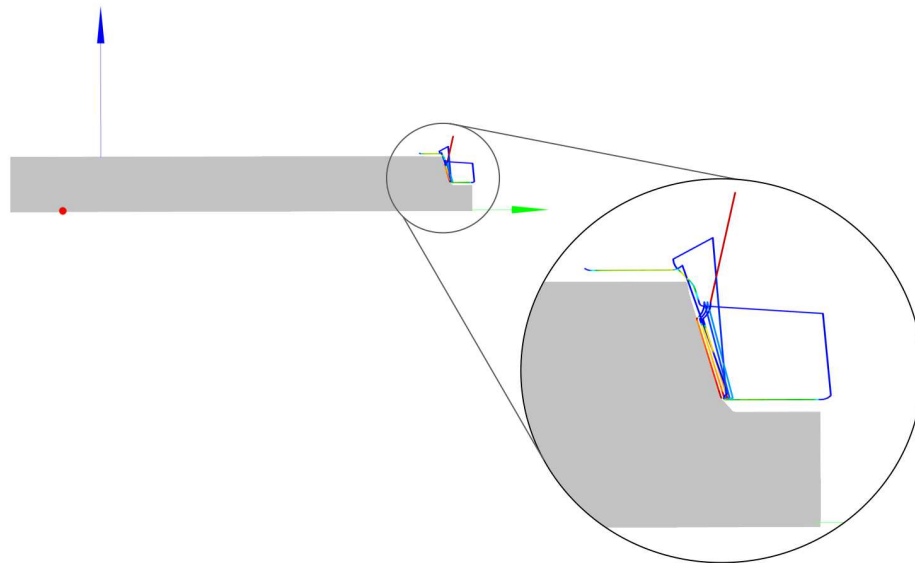
A turning operation example is shown in Figure 34. The red, green and blue arrows respectively represent the system coordinates. The toolpath data, which are zoomed in, are colored by the spindle load values from each sample. It is observed that the toolpath is in the y-z plane, i.e. $x = 0$.

Another important output of the data understanding phase is that the IPW was repositioned inside the machine tool before some of the processes so that the cuts can be performed more easily. When the user uploads the geometries of a product, as explained in section 5.1.1, only one STL file for the raw part and one for the finish part are uploaded, with no nominal geometries between processes. For this reason, the rotations in the IPW had to be reproduced in the software to simulate the cuts correctly.

6.3 DATA PREPARATION

The data preparation stage consisted of addressing the issue of the changes in the IPW position by process. Visualizing every IPW digital twin in the user interface in the same position provides a much better user experience, since features of the product will be in the same position for all digital twins when overlapped. Thus, it was decided that, instead of transforming the digital twin mesh position, the tooltip positions would be transformed by the opposite values of the digital twin. In this way, all digital twins remain in the same position while the cuts are properly simulated and the toolpath is

Figure 34 – Example of turning operation of the case study.



Source: gemineers archive.

shown in the correct position in the user interface.

To implement that, the model of the products saved in the database was modified to accept an array of nominal processes. The elements of this array are an ID, the process name and a object with the transformations.

The transformations object contains 6 keys: x , y and z , which indicate translations in the directions of each axis, and a , b and c , which indicate rotations around the axes x , y and z , respectively. The translation values must be informed in the same unit as the tooltip position acquired from the machine tool, while the rotations must be informed in degrees. It is important to note that all transformation values should be relative to the position of the product mesh uploaded during the product creation, instead of its position on the previous process.

An example nominal processes object is visible in Code Snippet A.2.1 of Appendix A. In the example, before process 1, the IPW is translated 30 units of distance in the negative direction of the z -axis, rotated 180° around the x -axis and 90° around the y -axis. On the other hand, no transformation is performed in the workpiece before process 2. Afterwards, a function was developed in the Cleaner to transform the tooltip position based on the nominal processes of the product.

Before executing the data processing services, features were added in the surfaces of the critical balloons provided by the client. The bounding geometries have been positioned so that they only intersect with the surface and toolpath samples of interest to the balloons. After all necessary features were created, the data was processed by the microservices, with IPW digital twins and KPIs as result. The digital twins are not

shown in this document due to non-disclosure agreements.

6.4 EVALUATION

Due to the confidential information contained in the case study, most achieved results have been omitted from this document. The following sections present the main remarks of the evaluation stage.

6.4.1 Process signals monitoring

To evaluate the process signals monitoring, the SPC charts detailed in section 5.2 were plotted for the calculated statistical measures. Due to the high correlation between cutting loads and surface integrity [46], the spindle load of the process was chosen for the monitoring evaluation.

By evaluating the control charts, it was possible to observe that the process signals monitoring correctly considers only the data samples inside the features' bounding geometries in the statistical measures calculations. Furthermore, the outlier detection method is able to indicate out-of-control loads which are correlated with the deviation measured with the touch probe simulated geometry deviation. However, there are cases where the load signal has very low correlation with the touch probe measurement.

In some features, the Western Electric and Nelson rules showed potential to detect out-of-tolerance patterns through the spindle load signal. Nevertheless, they were not consistently effective in it, with cases where an out-of-control sequence of load samples is not reflected on the deviation, and others where many out-of-tolerance parts did not show clear impacts on the load signal. The main potential causes for these issues are:

- **Uneven time intervals between samples:** Due to the high complexity and quality standards of the product, the manufactured workpieces are not machined at a constant rate. Since classic control charts are modeled assuming a consistent time interval between samples, many detected trends and anomalies may not indicate that the process is out of statistical control;
- **Missing data:** As explained in section 6.2, data of only two of four machine tools used in the product's manufacturing process were acquired. The missing data might have caused the detection of out-of-control patterns that are not consistent with reality or the loss of patterns that are consistent;
- **Lack of correlation between spindle load and deviation:** Although the correlation between loads and geometry deviation is widely acknowledged in machining processes, it may not be strong enough in the evaluated processes to identify

out-of-tolerance parts alone. Using a wider range of process signals can lead to more complete analyses.

6.4.2 Deviation monitoring

By comparing the monitoring results with the simulated digital twin, it is possible to attest that the monitoring results are consistent. Table 1 displays the Root Mean Squared Error (RMSE), Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) of the measurements for the two deviation monitoring approaches developed during the project.

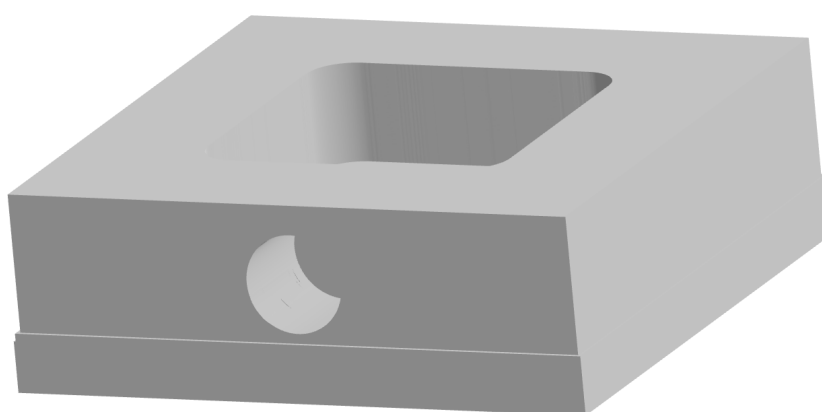
It is possible to observe that the second approach provided slight improvements in the results. Although the RMSE and MAE values are satisfactory, the MAPE is considerably high, which is a potential issue for features with larger deviation values.

Table 1 – Error metrics of showcase feature monitoring.

Metric	Value	
	Approach 1	Approach 2
RMSE (μm)	7.59	7.04
MAE (μm)	6.45	6.07
MAPE (%)	21.79	19.77

Source: author.

Figure 35 – Nominal geometries of showcase workpiece.



Source: gemineers archive.

7 CONCLUSION

The gemineers software, a platform for quality control of high precision machining processes, was enhanced during this project by the development of features for large-scale quality monitoring of product features. The project consisted of the design, development and validation of a solution that achieves this goal.

The design of the solution started from the product creation page. Developed in the already existing user interface of the software, the page is a 3-D interface where the user can upload and view nominal product geometry meshes, as well as select areas to monitor on their surface. These areas, called features, are limited by bounding geometries defined by the user. Through this, the user can then define tolerances for the geometric deviation in these features, as well as select process signals to monitor in it.

Furthermore, the data processing algorithms responsible for monitoring the deviation and process signals in each feature were developed. By using the digital twin generated by the machining simulation and the machine tool data acquired by the gemineers software, the algorithms are capable of evaluating the features individually by getting the intersection between the digital twin and the user-defined bounding geometries and between the toolpath and them. The algorithm outputs various statistical measures of the features, as well as a quality status KPI for each of them, and was integrated to the software as a new microservice.

A feature monitoring interface was developed on the main user interface, where signals monitored signals can be compared to the geometry deviation and other signals at each feature of every manufactured workpiece. Through this interface, it is also possible to identify signals which are out of statistical control, as well as trends and outliers in the manufacturing process. Moreover, an algorithm that evaluates the monitored signals and identifies out-of-control data points based on three statistical process control methods was developed and integrated to the software architecture, storing this data in the database as well.

To validate the monitoring algorithm developed, a case study was conducted at a client of gemineers. The case, which consisted of the manufacturing of low-pressure turbine disks by turning processes, proved to be quite challenging, with obstacles that significantly impacted the evaluation of results.

The evaluation of the process signal monitoring presented satisfactory results in the statistical measures calculation of signals inside bounding geometries. However, the anomaly and trend detection through SPC methods presented unsatisfactory results, given that no consistent correlation between the spindle load signal and the geometry deviation could be obtained from it. It is important to note, however, that the lack of data, the gaps in the data present and the inaccuracy of the output of the simulations

implemented in the software outside the project caused the evaluation to be severely limited. Therefore, the evaluation is not conclusive regarding the effectiveness of using the developed statistical process control algorithm for anomalies and trends detection.

Despite the limitations of the case study, an alternative example allowed the deviation monitoring algorithm to be properly evaluated, showing quite satisfactory results. This leads to the conclusion that deviation monitoring can bring significant advantages to the software user, as long as the simulation of the digital twin is properly carried on.

With the new features added to the software during the project, the engineering and quality teams of the company's clients have at their disposal a platform for the automatic evaluation of a product's functionality according to established tolerances. Its use has the potential to significantly increase the efficiency of the quality analysis process, as well as generating insights into improvements for the manufacturing line.

As future work on the subject, it is essential that the statistical process control algorithms are thoroughly evaluated with an adequate data set. For this to be achieved, it is necessary that data are acquired from a manufacturing line with a significant production volume, with little or no gaps.

As improvement potentials that may be further approached, it is worth highlighting the user interface, which can be refined to provide a better user experience and more information about the data, such as which condition caused a data point to be considered out of statistical control. A feature for freezing the control limits is also an alternative that can add significant value to the user because of the potential to evaluate the positive and negative impacts of planned changes in the process.

Further research can be carried on in multiple topics on the area of the project. A more complete deviation quality evaluation can be researched, taking into consideration not only the surface area in tolerance, but also the distribution of deviation values in the surface area. A larger diversity of bounding geometries for the features might also be integrated to the software, such as selecting regions of the surface using a lasso tool.

In addition, since samples with uneven intervals are common in the high precision machining industry, research on statistical process control methods for this kind of data has great importance, as well as research on statistical and learning models for fault prediction and classification.

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APPENDIX A – SOURCE CODE SECTIONS

This appendix contains sections of the source code that detail how the implementation of the project was performed in the software.

A.1 ANOMALY AND TREND DETECTION FUNCTIONS

```

1 def spc_tests(samples, type="oakland"):
2     import numpy as np
3     if type == "oakland":
4         out_of_control_indexes = oakland_tests(samples)
5     elif type == "western_electric":
6         out_of_control_indexes = western_electric_tests(samples)
7     elif type == "nelson":
8         out_of_control_indexes = nelson_tests(samples)
9     else:
10        raise ValueError("Type not identified.")
11    out_of_control_points = []
12    for rule in out_of_control_indexes.values():
13        out_of_control_points += rule
14    return sorted(set(out_of_control_points))

```

Code Snippet A.1.1 – Function developed to evaluate process signals based on SPC rules.

```

1 def oakland_tests(samples):
2     out_of_control_indexes = {}
3     mean = np.mean(samples)
4     std_dev = np.std(samples)
5
6     ual = mean+3*std_dev
7     lal = mean-3*std_dev
8     uwl = mean+2*std_dev
9     lwl = mean-2*std_dev
10
11    # Test 1. One point beyond Zone A
12    out_of_control_indexes["action_zone"] += sorted(set([idx for idx in
13    range(len(samples)) if samples[idx] > ual or samples[idx] < lal]))
14
15    # Test 2. Two consecutive points between zone A and B
16    for idx in range(0, len(samples)-1):
17        consecutive_points = samples[idx:idx+2]
18        warning_zone_indexes = [subset_idx for subset_idx in range(len(
19    consecutive_points)) if consecutive_points[subset_idx] > uwl or
20    consecutive_points[subset_idx] < lwl]
21        if len(warning_zone_indexes) >= 2:

```

```

19         out_of_control_indexes["warning_zone"] += [idx + subset_idx
20         for subset_idx in warning_zone_indexes]
21     return out_of_control_indexes

```

Code Snippet A.1.2 – Function developed to evaluate samples using the criteria proposed by Oakland [32].

```

1  def western_electric_tests(samples):
2      out_of_control_indexes = {}
3      mean = np.mean(samples)
4      std_dev = np.std(samples)
5
6      upper_zone_a = mean+3*std_dev
7      lower_zone_a = mean-3*std_dev
8      upper_zone_b = mean+2*std_dev
9      lower_zone_b = mean-2*std_dev
10     upper_zone_c = mean+std_dev
11     lower_zone_c = mean-std_dev
12
13     # Test 1. One point beyond Zone A
14     out_of_control_indexes["test_1"] = sorted(set([idx for idx in range(
15     len(samples)) if samples[idx] > upper_zone_a or samples[idx] <
16     lower_zone_a]))
17
18     # Test 2. Two out of three points in a row in Zone A or beyond
19     test_2 = []
20     for idx in range(0, len(samples)-2):
21         consecutive_points = samples[idx:idx+3]
22         points_over_upper_limit = [subset_idx for subset_idx in range(
23         len(consecutive_points)) if consecutive_points[subset_idx] >
24         upper_zone_b]
25         points_under_lower_limit = [subset_idx for subset_idx in range(
26         len(consecutive_points)) if consecutive_points[subset_idx] <
27         lower_zone_b]
28         if len(points_over_upper_limit) >= 2:
29             test_2 += [idx + subset_idx for subset_idx in
30             points_over_upper_limit]
31         if len(points_under_lower_limit) >= 2:
32             test_2 += [idx + subset_idx for subset_idx in
33             points_under_lower_limit]
34     out_of_control_indexes["test_2"] = sorted(set(test_2))
35
36     # Test 3. Four out of five points in a row in Zone B or beyond
37     test_3 = []
38     for idx in range(0, len(samples)-4):
39         consecutive_points = samples[idx:idx+5]

```

```

32     points_over_upper_limit = [subset_idx for subset_idx in range(
len(consecutive_points)) if consecutive_points[subset_idx] >
upper_zone_c]
33     points_under_lower_limit = [subset_idx for subset_idx in range(
len(consecutive_points)) if consecutive_points[subset_idx] <
lower_zone_c]
34     if len(points_over_upper_limit) >= 4:
35         test_3 += [idx + subset_idx for subset_idx in
points_over_upper_limit]
36     if len(points_under_lower_limit) >= 4:
37         test_3 += [idx + subset_idx for subset_idx in
points_under_lower_limit]
38     out_of_control_indexes["test_3"] = sorted(set(test_3))
39
40     # Test 4. Eight points in a row in Zone C or beyond
41     test_4 = []
42     for idx in range(0, len(samples)-7):
43         consecutive_points = samples[idx:idx+8]
44         if all(point > mean for point in consecutive_points) or all(
point < mean for point in consecutive_points):
45             test_4 += range(idx, idx+8)
46     out_of_control_indexes["test_4"] = sorted(set(test_4))
47
48     return out_of_control_indexes

```

Code Snippet A.1.3 – Function developed to evaluate samples using the Western Electric rules.

```

1 def nelson_tests(samples):
2     out_of_control_indexes = {}
3     mean = np.mean(samples)
4     std_dev = np.std(samples)
5     samples_derivative = np.concatenate((np.array([0]), np.diff(samples)
))
6
7     upper_zone_c = mean+std_dev
8     lower_zone_c = mean-std_dev
9
10    western_electric_indexes = western_electric_tests(samples)
11
12    # Test 1. One point beyond Zone A (Western Electric #1)
13    out_of_control_indexes["test_1"] = western_electric_indexes["test_1"
]
14
15    # Test 2. Nine points in a row in Zone C or beyond
16    test_2 = []
17    for idx in range(0, len(samples)-8):
18        consecutive_points = samples[idx:idx+9]

```

```
19     if all(point > mean for point in consecutive_points) or all(
20 point < mean for point in consecutive_points):
21         test_2 += range(idx, idx+9)
22         out_of_control_indexes["test_2"] = sorted(set(test_2))
23
24 # Test 3. Six points in a row steadily increasing or decreasing
25 test_3 = []
26 for idx in range(0, len(samples_derivative)-5):
27     derivative_of_consecutive_points = samples_derivative[idx:idx+6]
28     if all(derivative > 0 for derivative in
29 derivative_of_consecutive_points) or all(derivative < 0 for
30 derivative in derivative_of_consecutive_points):
31         test_3 += range(idx, idx+6)
32         out_of_control_indexes["test_3"] = sorted(set(test_3))
33
34 # Test 4. Fourteen points in a row alternating up and down
35 test_4 = []
36 for idx in range(0, len(samples_derivative)-13):
37     derivative_of_consecutive_points = samples_derivative[idx:idx+14
38 ]
39     is_alternating = True
40     for subset_idx in range(0, 13):
41         # If the derivatives of two consecutive points have the same
42         # signal, they are not alternating
43         if derivative_of_consecutive_points[subset_idx] *
44 derivative_of_consecutive_points[subset_idx+1] >= 0:
45             is_alternating = False
46             break
47     if is_alternating:
48         test_4 += range(idx, idx+14)
49         out_of_control_indexes["test_4"] = sorted(set(test_4))
50
51 # Test 5. Two out of three points in a row in Zone A or beyond (
52 Western Electric #2)
53 out_of_control_indexes["test_5"] = western_electric_indexes["test_2"
54 ]
55
56 # Test 6. Four out of five points in a row in Zone B or beyond (
57 Western Electric #3)
58 out_of_control_indexes["test_6"] = western_electric_indexes["test_3"
59 ]
60
61 # Test 7. Fifteen points in a row in Zone C (above and below
62 centerline)
63 test_7 = []
64 for idx in range(0, len(samples)-14):
65     consecutive_points = samples[idx:idx+15]
```

```
55     if all(point < upper_zone_c and point > lower_zone_c for point
56     in consecutive_points):
57         test_7 += range(idx, idx+15)
58         out_of_control_indexes["test_7"] = sorted(set(test_7))
59
60     # Test 8. Eight points in a row on both sides of centerline with
61     none in Zones C
62     test_8 = []
63     for idx in range(0, len(samples)-7):
64         consecutive_points = samples[idx:idx+8]
65         if (all(point > upper_zone_c or point < lower_zone_c for point
66         in consecutive_points) and
67         (any(point > upper_zone_c for point in consecutive_points)
68         and any(point < lower_zone_c for point in consecutive_points))):
69             test_8 += range(idx, idx+8)
70             out_of_control_indexes["test_8"] = sorted(set(test_8))
71
72     return out_of_control_indexes
```

Code Snippet A.1.4 – Function developed to evaluate samples using the Nelson rules.

A.2 DATA PREPARATION FUNCTIONS

```
1  [
2  {
3      "_id": "7ca78a48-6536-4910-be91-d4fc2c63e15c",
4      "nominalprocessname": "1",
5      "transformations": {
6          "x": 0, "y": 0, "z": -30,
7          "a": 180, "b": 90, "c": 0
8      }
9  },
10 {
11     "_id": "99f3d54f-e193-4940-8949-bad68172ed16",
12     "nominalprocessname": "2",
13     "transformations": {
14         "x": 0, "y": 0, "z": 0,
15         "a": 0, "b": 0, "c": 0
16     }
17 }
18 ]
```

Code Snippet A.2.1 – Example of nominal processes object.