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FACULTY OF POWER AND AERONAUTICAL ENGINEERING

Ph.D. Thesis

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Engineering and inspection problems study for Turbine Guide Vane Mechanical Component

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WARSAW 2021

To my son

Mojemu synowi

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Abstract

Turbine guide vane represents the aero shape components family used to build big and powerful engines. Even now, in the XXI century, constant development could reach some barriers and difficulties to solve.

Thermal scaling for a mechanical component is a very crucial and complex process. Turbine guide vane is engineered and calculated to work in high temperatures. Production shape is different and shall be reversed to match thermal growth deformations. All components must be precisely engineered to reach long-term work conditions as every replacement is usually strictly scheduled in the turbine life cycle. The thesis proposes an automatic iterative process in the CAD-CAE environment to obtain a reliable shape considering all configuration constraints. The mentioned method allows for the actual thermal reverse mapping of the element from the beginning to the end of the entire prototyping stage.

Many CAD systems are available in the industry, so a neutral data format allows exchanging configuration requirements between machines, systems, and third-party companies. A definition translated to a neutral format should contain the same number of geometry details as the original CAD file and allow production and inspection of the final component. Requirements and guidelines should be distributed globally to satisfy all users. A proprietary set of requirements was proposed and automated using predefined CAD tools. Risks resulting from translation inaccuracies, missing data, or inappropriate file format selection have been identified.

CMM touch technology is still the most trustworthy type of inspection. Massive measurements are constantly forcing for new simplifications and enhancements. The key for a modern approach is to understand mechanical objectives, production limitations and focus on the most critical areas. The most critical measurement aspects were defined in this work, and a hybrid method was proposed to inspect the horizontal profiles and the vertical trend line simultaneously.

3D scanning is a modern method that may supersede CMM nowadays. There are still some areas that are not standardized, and there are some traps for inexperienced operators. Knowing the weaknesses, we have a chance to introduce new algorithms to support automatic and trustworthy inspections. Small surfaces distortions could have significant meaning for the entire process. The thesis proposes an original algorithm for filtering small areas of the chamfer and blends. Based on the conducted experiments, the measurement accuracy obtained can be comparable with the CMM method.

This work focuses on part-specific problems hidden in small sub-processes during the prototyping – production – inspection lifecycle. All these aspects are strictly correlated with each other. A proper data translation shall be secured from the very beginning of the part development to the last inspection process. Enhancements in measurements allow confirming the configuration intent in practice. Thermal translation allows us to predict the actual part behavior. All these aspects secure the right and tight shape tolerance range to build an efficient engine.

Keywords: gas turbine, turbine guide vane, product manufacturing information, CAD, CMM, 3D optical scanning, hot to cold transformation,

Streszczenie

Łopatka kierownicza jest reprezentatywnym przykładem rodziny elementów o kształcie aerodynamicznym, które są wykorzystywane do budowy wielkich i wydajnych silników. Nawet teraz, w XXI wieku, wciąż możemy napotkać wiele trudności stanowiących interesujące wyzwania do rozwiązania.

Skalowanie termiczne dla elementu mechanicznego jest bardzo ważnym i złożonym procesem. Łopatka kierownicza jest zaprojektowana i obliczona do pracy w wysokiej temperaturze. Kształt produkcyjny jest inny i należy go odwrócić w celu dopasowania do odkształceń cieplnych. Wszystkie te aspekty muszą być precyzyjnie zaprojektowane, aby odpowiadały długoterminowym warunkom pracy. Czas wymiany bądź naprawy części jest ściśle określony w cyklu życia turbiny. W niniejszej rozprawie zaproponowano automatyczny proces iteracyjny w środowisku CAD-CAE w celu uzyskania wiarygodnego kształtu z uwzględnieniem wszystkich ograniczeń projektowych. Metoda pozwala na rzeczywiste odwzorowanie elementu po konwersji termicznej od początku do końca całego etapu prototypowania.

W przemyśle dostępnych jest wiele systemów CAD, a neutralny format danych umożliwia wymianę wymagań konfiguracyjnych między maszynami, systemami i firmami zewnętrznymi. Definicja przetłumaczona na format neutralny powinna zawierać taką samą liczbę szczegółów dla geometrii, jak oryginalny plik CAD, a co za tym idzie umożliwiać produkcję i kontrolę końcowego komponentu. W tym celu należy określić wymagania i wytyczne dla użytkowników z całego świata. Zaproponowano autorski zestaw wymagań i poddano go automatyzacji przy użyciu predefiniowanych narzędzi CAD. Zidentyfikowano zagrożenia płynące z niedokładności translacji, pominięcia danych lub nieodpowiedniego doboru formatu plików.

Metoda współrzędnościowa CMM jest nadal najbardziej godnym zaufania rodzajem inspekcji. Mnogość przeprowadzanych pomiarów wymusza nowe, nawet drobne uproszczenia i ulepszenia. Kluczem do nowoczesnego podejścia jest zrozumienie warunków pracy części i skupienie się na najbardziej krytycznych obszarach. W tym celu zdefiniowano najważniejsze aspekty pomiarowe i zaproponowano metodę hybrydową do jednoczesnej inspekcji profili poziomych i pionowej linii trendu.

Skanowanie 3D to nowoczesna metoda, która ma możliwość zastąpić metodę współrzędnościową CMM. Niestety, nadal można tu zidentyfikować obszary, w których dokładność pomiarowa jest mocno wątpliwa. Znając te słabości, jest szansa na wprowadzenie nowych algorytmów wspierających automatyczne i godne zaufania inspekcje. Małe zaburzenia powierzchni mogą mieć istotne znaczenie dla całego procesu pomiarowego. W niniejszej rozprawie zaproponowano autorski algorytm filtrowania małych powierzchni typu fazy i zaokrąglenia. Na podstawie przeprowadzonych doświadczeń, uzyskano dokładność pomiarową uzyskiwaną dotychczas głównie dla metody CMM.

Praca ta koncentruje się na specyficznych problemach części ukrytych w małych pod procesach podczas cyklu prototypowania – produkcji – kontroli. Wszystkie te aspekty są ze sobą ściśle skorelowane. Prawidłowa translacja danych powinna być zapewniona od początku prototypowania części aż do finalnej kontroli jakości. Udoskonalenia pomiarów pozwalają na praktyczne potwierdzenie założeń projektowych. Translacja termiczna pozwala przewidzieć rzeczywiste zachowanie części. Wszystkie te aspekty zapewniają właściwy zakres tolerancji kształtu w celu zbudowania wydajnego silnika.

Słowa kluczowe: turbina gazowa, lopatka kierownicza, cyfrowa definicja produktu, CAD, CMM, 3D skan, skalowanie cieplne,

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List of abbreviations

ASME	- **A**merican **S**ociety of **M**echanical **E**ngineers
CAD	- **C**omputer **A**ided **D**esign
CMM	- **C**oordinate **M**easuring **M**achine
DPI	- **D**ye **P**enetrant **I**nspection
FEM	- **F**inite **E**lements **M**ethod
FPI	- **F**luorescent **P**enetrant **I**nspection
GD&T	- **G**eometric **D**imensioning **and** **T**olerancing
IGES	- **I**nitial **G**raphics **E**xchange **S**pecification
ISO	- **I**nternational **O**rganization for **S**tandardization
MBD	- **M**odel **B**ased **D**efinition
MBE	- **M**odel **B**ased **E**nterprise
NDT	- **N**on-**D**estructive **T**esting
PLM	- **P**roduct **L**ifecycle **M**anagement
PMI	- **P**roduct **M**anufacturing **I**nformation
STEP	- **St**andard for the **E**xchange of **P**roduct Model Data
STL	- **St**ereo**l**ithography

1. Introduction

1.1. Gas Turbine hot gas section overview

Turbine hot gas path area components (Fig.1.1) are essential parts that work in very aggressive conditions like high temperatures and corrosive atmosphere[68]. Their engineering requires precisive predictions of all crucial work variables and manufacturing capabilities. They need to be engineered as thermally deformed shapes. All configuration objectives are related to full load and maximum temperature conditions [12].

Gas turbines belong to the biggest machines developed by humanity, where thermal growth values are visible to the naked eye. Uncontrolled thermal deformation can lead to severe failures in the overall assembly, affect engine efficiency, overlap, or collide with interfacing parts.

This work is focused on a static part representative – a turbine guide vane.

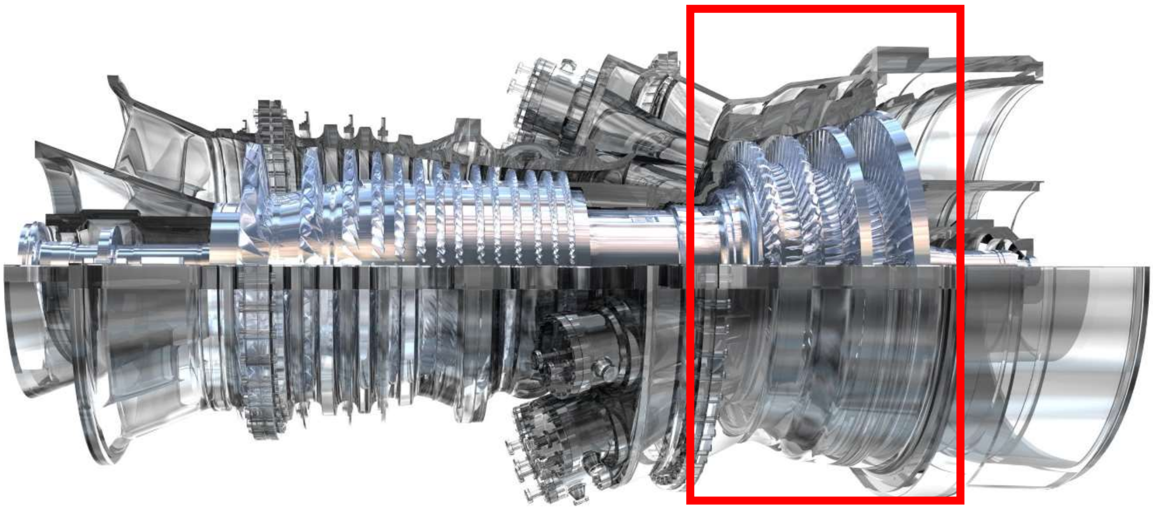
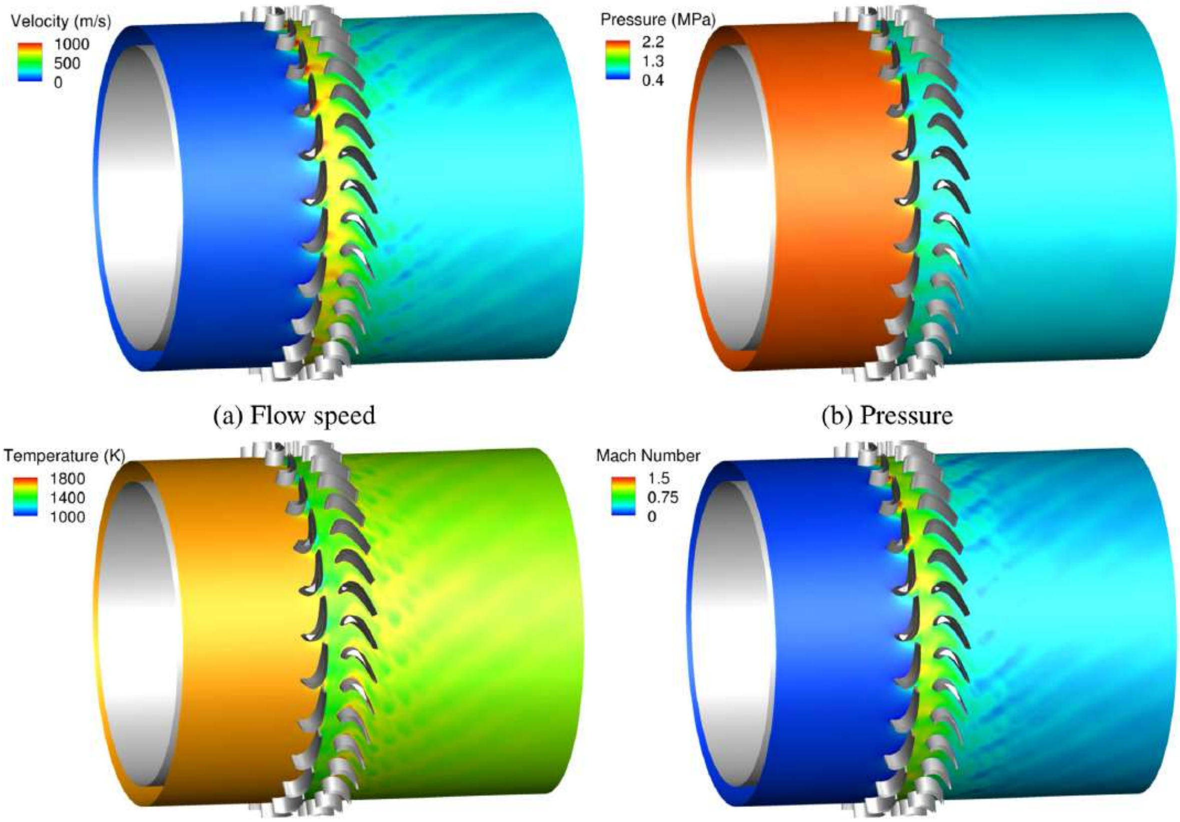


Fig.1.1. Gas turbine hot gas path section[86].

1.2. Turbine guide vane overview.

Turbine guide vanes belong to the most complicated components to engineer and manufacture. Because of the complexity, fast and cheap methods of manufacture have no application here. The most common method is to cast a part, machine, weld/braze and coat at the end. 3D printing still has a marginal impact, but we can expect more researches in this area shortly.

Turbine guide vanes control flow directions and intensity[12, 72]. Based on Bernoulli's principle, the flow leaving turbine guide vane will have higher velocity but lower pressure and temperature (Fig.1.2). This flow drives through turbines blades and rotates the rotor of the machine. In the direct correlation, flow scheme and distribution affect engine efficiency.



(a) Flow speed (b) Pressure

(c) Temperature (d) Mach number

Fig.1.2. Flow variables inside a gas turbine[80].

All airfoils shall be precisely and equally distributed in a turbine assembly (Fig.1.3). An extensive engineering issue is where thermal deformation affects this perfect distribution – a cold production shape distribution must be different, taking into account this phenomenon. That is why the first turbine stage is commonly developed as one airfoil vane (singlet), which is easier to control and can be re-positioned. The following stages are colder than it, so there, multi-airfoil vanes are typically installed.

The turbine guide vane has a straightforward base construction, and we can highlight just three major parts –outer platform, inner platform, and airfoil (Fig.1.4). Both platforms have a surface connected directly to the airfoil shape called a gas path surface. For this work, the terms outer and inner gas path surface will be used.

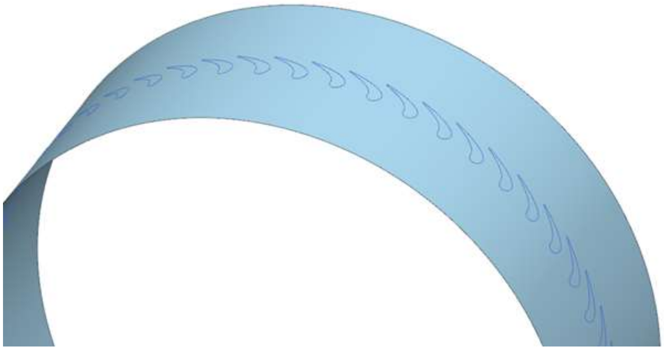


Fig.1.3. A 3D section through the set of turbine guide airfoils.

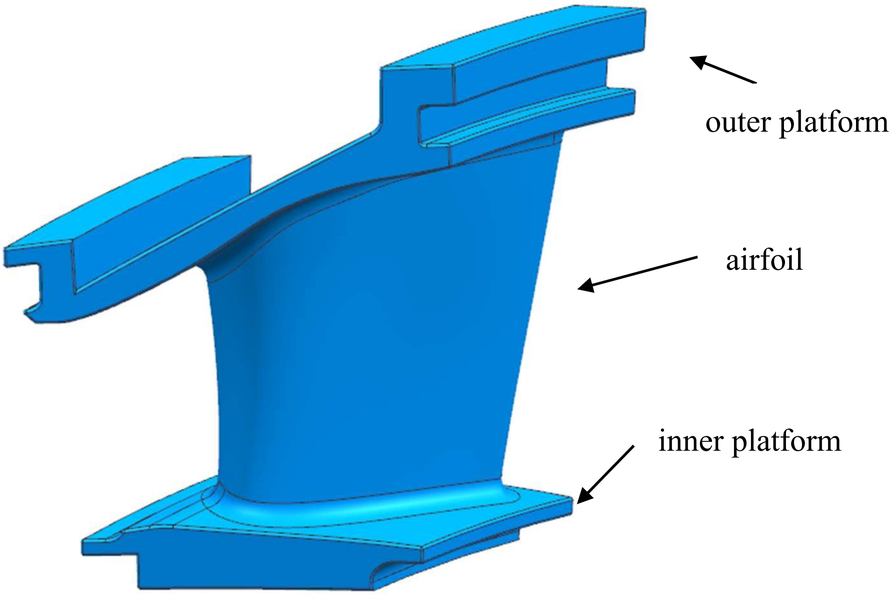


Fig.1.4. Turbine guide vane example.

We can divide vanes into some groups:

- **Singlet** – a vane with only one airfoil – able to re-stagger airfoil engine position
- **Multiple airfoils vanes –** doublet (two airfoils), triplet (three airfoils), quadruplet (four airfoils), et cetera.

Another division for turbine vanes is related to additional cooling so that we can highlight:

- **cooled** vanes (with and without an internal core)
- **uncooled**, solid vanes

The last division is related to additional barrier coating so that we can highlight:

- **coated** vanes (with one or many layers)
- **uncoated** vanes

Typically, the first stage of vanes is built using coated cooled singlets, middle stages cooled uncoated doublets/triplets, and the last row usually is uncoated uncooled triplet/quadruplet. Every additional vane modification is costly and time-consuming. Those variations are strictly related to working conditions, reviewed at the beginning of the project (Fig.1.5).

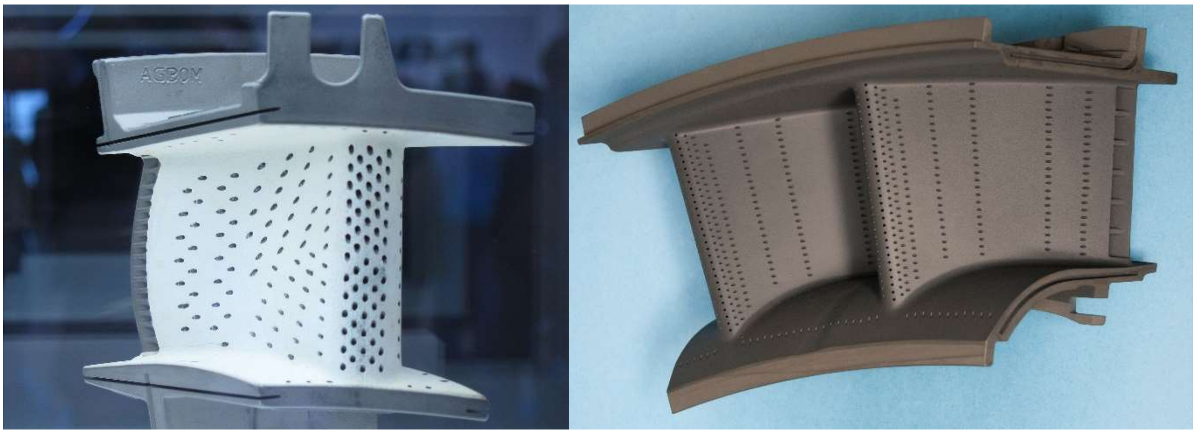


Fig.1.5. Different types of turbine guide vane components [101, 102].

This work is focused on a component with a singular airfoil (singlet) with a cooling hole pattern, as an example of the most complicated and challenging vane type.

1.3. Aero shape

All aero-shaped components like blades and vanes need to match restrictive aero requirements. Airfoil surfaces must have higher mathematical requirements than other surfaces. A typical - simplified - CAD surface is created based on equations needed to compromise good mathematical shape and good software performance for a real-time model visualization [78]. Parametrical (editable) features belong to objects created in CAD software by available tools and simplified mathematic. That is briefly how modern software is written to satisfy clients all over the globe, still ensuring good graphical performance. From simple models to the top assemblies, it shall be feasible to display every detail and rotate in real-time by users.

In computer-aided design and computer graphics[19][70], curves (Fig.1.6) and freeform surfaces (Fig.1.7) are constructed as linear combinations of B-splines with a set of control points. These elements are created from a group of standalone Bezier curves and interpolated to visualize a complex shape. All those simple splines are related to each other by continuity. There are two standard spline/surface continuities: C – mathematical and G – geometrical (less restrictive). For smoothness purposes, CAD environments typically use simplified requirements to match geometrical continuities. We have here G0 (most common, two curves/surfaces that shares a boundary)[43], G1 (tangent connection of two curves/surfaces) or G2 (two curves/surfaces that have the same curvature values at the joint) level of continuity. G3 continuity is developed to secure the smoothness on the whole length, so the curves/surfaces look like a one feature. The joint area is invisible, can be designated only by a math formula.

These operations commonly belong to advanced surface modeling (Fig.1.8).

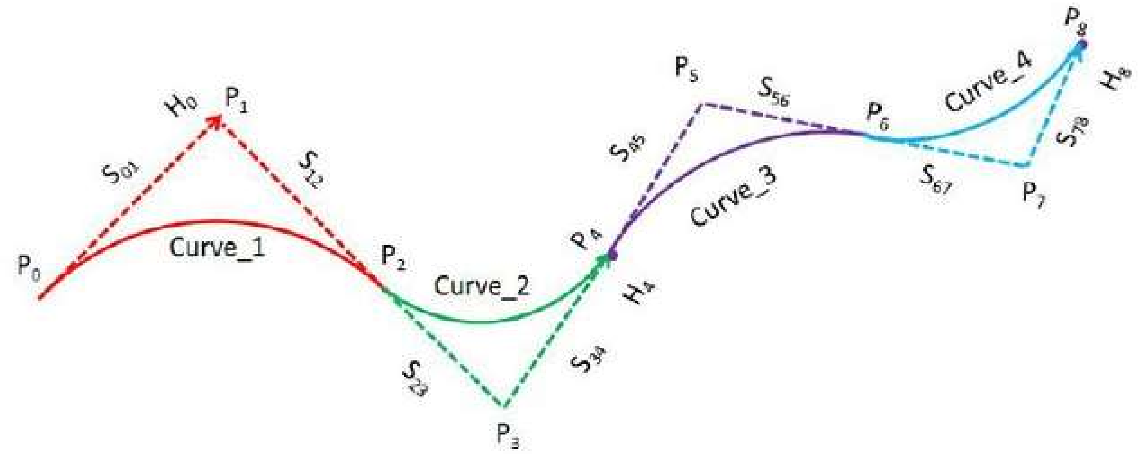


Fig.1.6. B-Spline curve example [73]

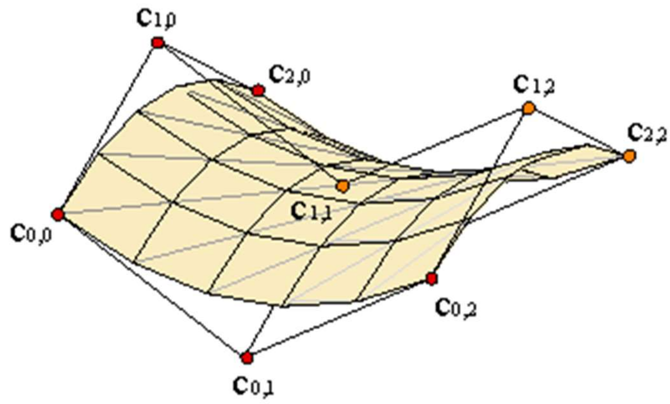


Fig.1.7. B-Spline surface example [100]

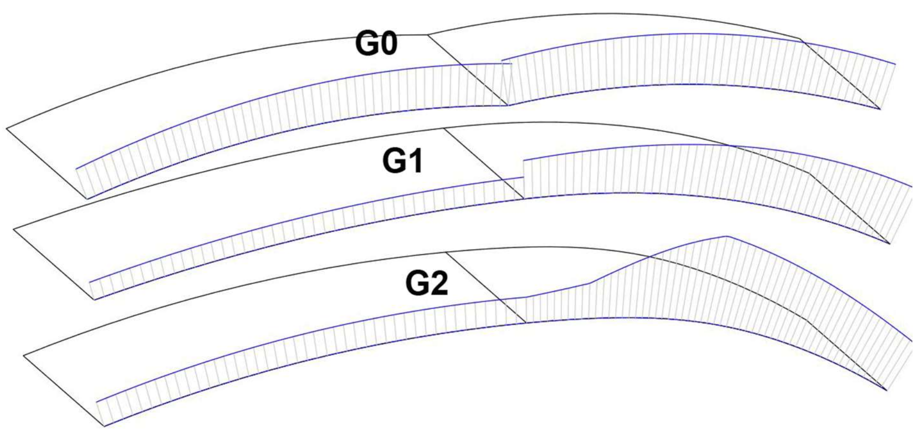


Fig.1.8. Geometrical Continuity [43]

Mathematical continuity is defined based on the tangency of two corresponding splines and matching curvature vectors. C0 connection shares the same point where join (simple connection)[83], C1 has continuous derivative (same geometric slopes at connection joint)(Fig.1.9), C2 second derivative (center of curvature at connection joint is the same) [78]. There are some CAD restrictions, not only related to continuity. Rho (a ratio between the projected height of the apex curve and control curve) is usually fixed to be 0.5, and not every CAD allows to change or manipulate with this parameter (Fig.1.10).

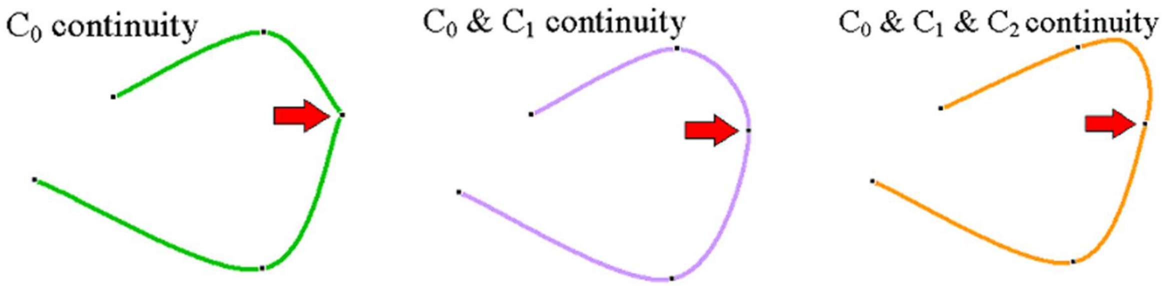


Fig.1.9. Mathematical continuity [83]

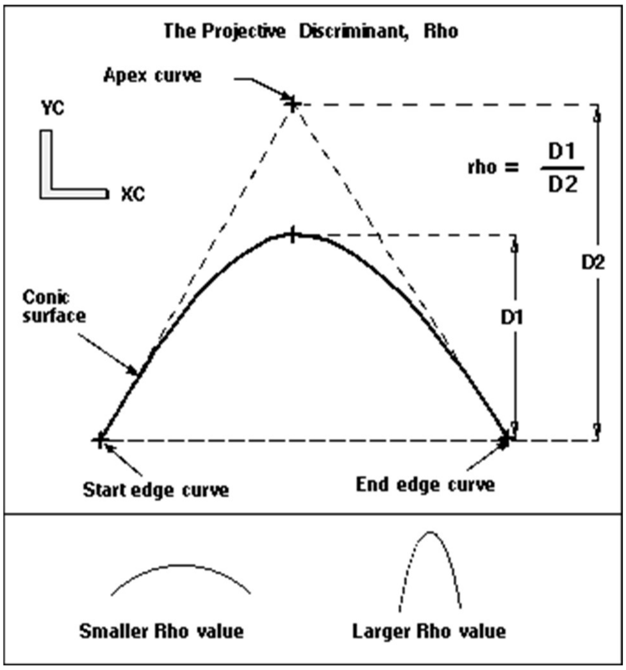


Fig.1.10. Rho interpretation [113]

Airfoil shape must be smooth and continues and match restrictive mathematical requirements, starting from C2 (second derivative) going even higher to derivates like C3 and C4. Higher derivatives create a smooth shape that looks like a single complicated shape, still constructed from smaller B-splines. CAD systems commonly are not supporting those high continuities requirements. That is why airfoil shape should be prepared in external software (typically not commercial but created internally by companies). There are many CAD tools to inspect its shape continuity. Still, the easiest way is to display peaks, knots, and combs for the overall continuity. In Fig.1.11, there is an example of a “poor” airfoil shape created by splines using essential tools in NX CAD software; black color shows smoothened spline created outside CAD environment and imported as non – parametric feature. Like all other CAD’s, NX can open and display more complicated geometry and can inspect it.

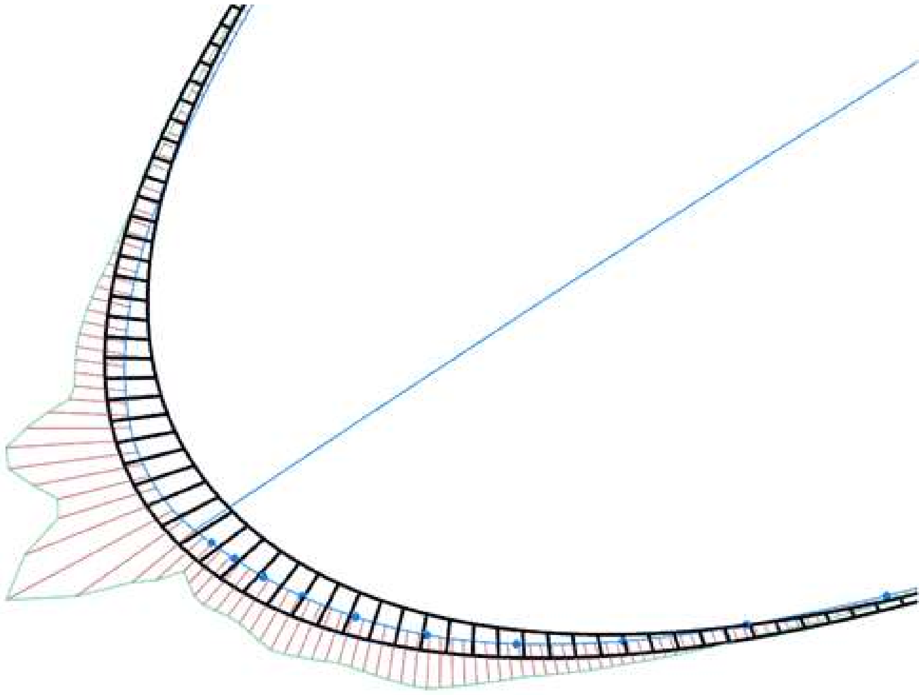


Fig.1.11. Airfoil leading edge shape (initial example in blue/green/red) adjusted by an external software exceeding CAD capability (in black).

Airfoil must be well described not only in 2D but on the overall 3D surface. It means that the engineer shall use a limited number of 2D sections to maintain good continuity. Too many sections can introduce bad continuities in model sweeping. There should be a compromise to create a good quality surface. Typically, 3-5 sections should be enough, but it depends on the overall part length, and the largest airfoils would need much more—a part-specific scenario for long rotating blades.

Again, the better solution is to create an overall airfoil surface in an external tool or software. Two significant reasons are crucial. First, as mentioned previously, the swept surface will use limited math available in CAD software, which can cause distortions. Second, similar tools for sweeping the same 2D sections in different CADs can get different results, even outside manufacturing tolerances [18]. That could be a severe trap for not experienced engineers. The only reasonable way is to use tessellation via neutral format files like STEP or IGES. The translation outside the original CAD software is gentle and needs to be done carefully with precisely chosen tolerances.

These restrictions are crucial, and modern companies are developing their tools to create base airfoil geometry and transfer the final shape to the CAD environment. This collection of conditions and details are essential for the thesis of this work. Airfoil aero geometry is a complex shape that needs to be carefully engineered, manufactured and inspected.

1.4. Throat

A 2D throat is the smallest distance between two airfoil splines obtained from the same plane (Fig.1.12)[68]. That is very important to inspect a real part and to compare it with the CAD model. There are many different philosophies on how to define and calculate throat areas on a real part. The entire set of components in the turbine can be assembled with an improved flow scheme. As stated in the introduction section, according to Bernoulli's principle, the flow will be changed in this place to have a higher velocity with the pressure and temperature drop (Fig.1.13). That is why its engineering and measurement process is secured by companies with many patents[13, 52, 66] as the critical aspect to achieve assumed engine efficiency.

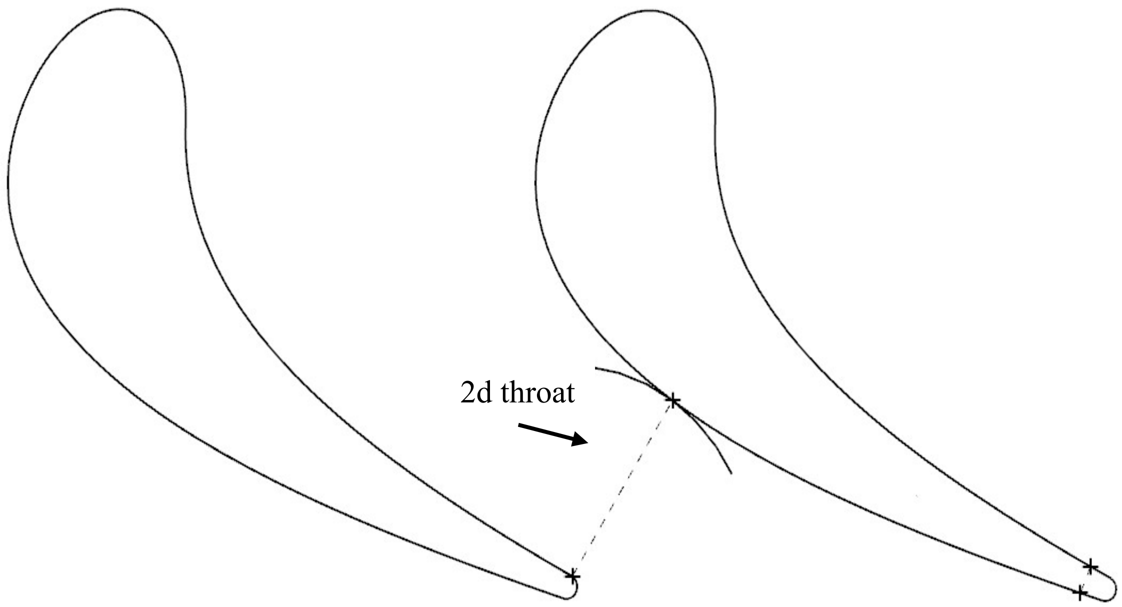


Fig.1.12. A 2D throat example[39].

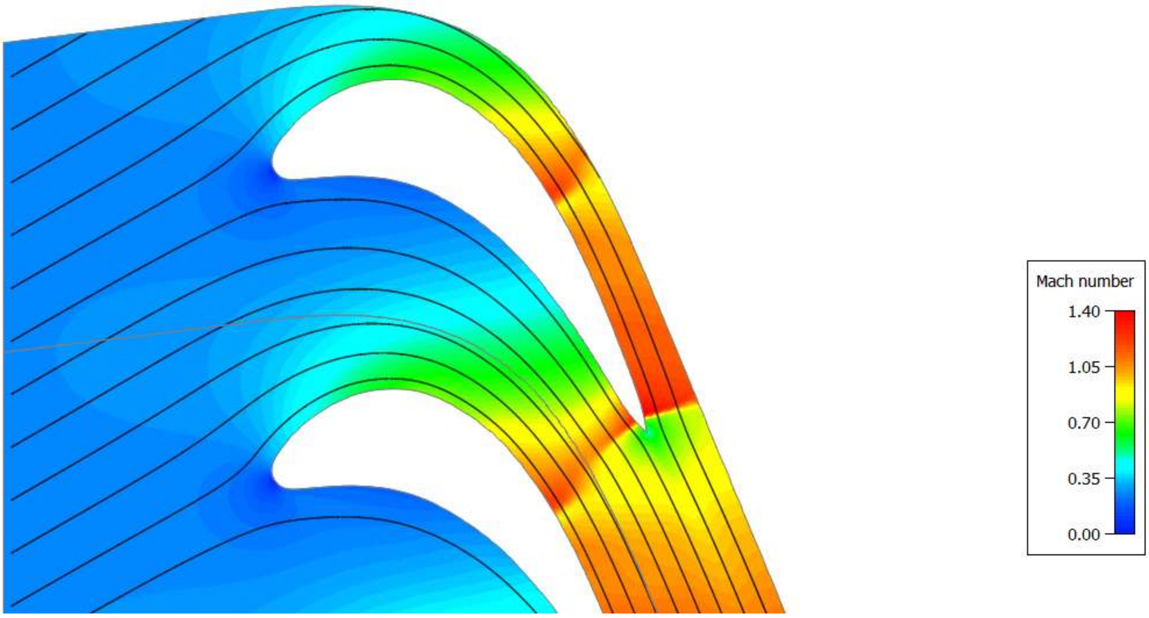


Fig.1.13. Throat impact on the local flow change (example)[42].

Some terms can be highlighted there:

- **Linear throat** – 2D line on a radial section which defines local throat height
- **Throat Area** – This surface is created from the infinite linear throats obtained from the inner to the outer platform.
- **Radial throat** – the vertical distance between the top and bottom highest peak lied on the throat surface

1.5. Thermal scaling problems

Thermal scaling for a mechanical component is a very crucial and complex process. The part is developed and calculated to work in high temperatures while manufactured to a deformed "initial" shape for an ambient temperature condition.

Surface continuities and aero shape restrictions shall be met for manufacturing purposes after hot to cold reversing conversion. Complex components are being manufactured by casting methods which are prone to shape errors[84]. Aero-shaped surfaces (airfoil, flow path surfaces) cannot be fixed, machined, or repaired; that is why precision in CAD engineering is critical here. The 3D CAD model is the primary source for manufacturers, as 2D documentation can no longer secure the required accuracy (as was done before the CAD era)[71]. High precision math is not intended to be widely distributed on technical documents. Many standards like ISO or ASME [88, 90] state that drawing shall be readable by any user worldwide, so simplifying is crucial.

Deformation can be performed easily in CAE - FEM software, but unfortunately, this translation type will not cover precisive details [57]. Wall thickness, cooling holes shapes, and other details are standardized for manufacturing at room temperature. CAE deformed model is never intended to be a manufactured model. FEM method benefits can be used as a step of a bigger loop, which will be described in this work. Precise engineering needs geometry perfection, which is crucial for a 3D solid geometry CAD creation. FEM analysis can prove or adjust production shape. For this work, the term "cold" will be used for a room temperature (20 °C (68 °F)), and a "hot" term will be used for working temperatures like 1000 °C (1832 °F) and even more.

All of these bring us to the point that hot to cold conversion shall be done under one available CAx multi-system or a shared math environment. Switching between standalone CAD and CAE software could be very risky, as deformation can stratify shape deviation errors and introduce not scalable issues to the final configuration. This work is made using NX 12 CAD and CAE shared environment with Ansys solver. That shall assure reliable results for thermal shape transformation.

1.6. CAD Data Exchange Overview

Modern companies have been turning into model-centric engineering for years. Old 2D drawings are commonly used only for archived data and to preserve the history of production or product lines. All newly created products are based on 3D models, which are now the primary source for all "unclear" regions of the definition[106].

The times where primary 2D definition print was accessible and readily comprehensible to all collaborators are over. The primary source of data – a 3D model - is always created in a specific CAD environment, which can be an impassable barrier for vendors working with different systems or, more commonly, with many other clients using different standards[44].

It is noticeable that companies are developing more and more convenient solutions for data exchange, like 3D PDFs[56, 110] or even external tools for CAD visualization[107][91]. Some free or relatively cheap applications to open and see the CAD file without any possibility of modifying or re-exporting (created mainly by original CAD developers)[108] are available in the industry. All have the same significant disadvantage - we lose the main 3D benefit to re-use a CAD solid for manufacturing or inspection purposes. 3D visualization is only for reference and is not intended for further processing.

As this visualization is sent straight to the production plant, there is a need to translate original data into a neutral format of the same quality level, without any distortions which may lead to an error or failure[10].

There are three ways to help to deliver data externally:

- direct model translation (preferred)
- neutral file exchange (compromise)
- third-party translators

Translating the data directly from a source CAD system, rather than importing it into other, uncontrolled environments, seems to be the only reasonable method. There are many CAD systems available in the industry, so a neutral data format secures the ability to exchange configuration requirements both inside the organization and with all the external suppliers[11].

1.6.1. CAD Data Exchange typical problems

A specific CAD file imported to a different CAD system can contain many redundant and unclear features[18, 23]. Some extra solids, surfaces, lines, datum planes, and other features with only a supportive function should be filtered from the visualization (Fig.1.14).

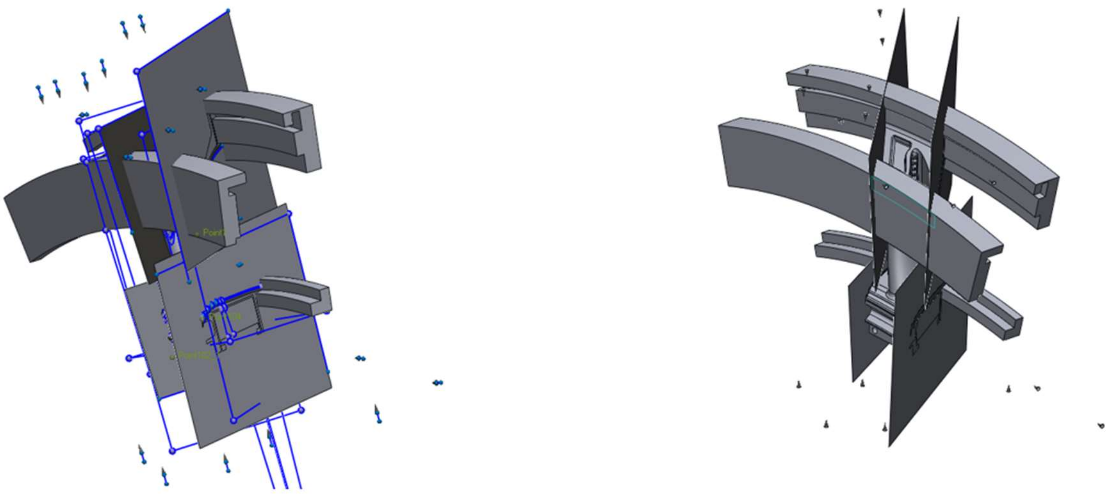


Fig.1.14. Example of a CAD File imported to another system. a) total data, b) solids and surfaces only

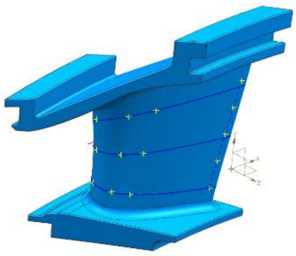
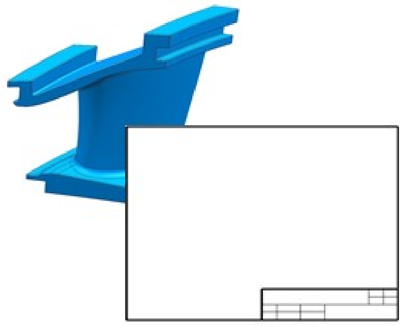
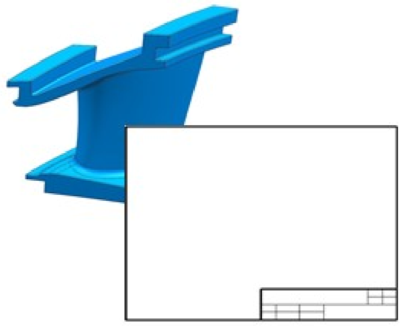
Part – 3D CAD Specification	Production – 2D drawing with 3d solid	Inspection - 2D drawing with 3d solid
		

Fig.1.15. A proper part definition cannot neglect the new trends to later processes, such as a quality inspection.

Modern data translation cannot neglect additional information for manufacture and inspection in the end (Fig.1.15)[8, 26, 27, 31, 34, 63]. Just a solid body is not enough to accurately reproduce the engineered part. All kinds of information, like a datum system or CMM/3D scan point coordinates, are needed to describe and build a fully functional component, so they need to be translated too[34]. This definition will supersede all classical drawing types (2D and 3D – since 3D is typically a more "elegant" copy of traditional drawing). When 3D scan inspection is more and more popular, a bridge between the engineering intent, manufacturing, and inspection needs to be strengthened (Fig.1.16)[36].

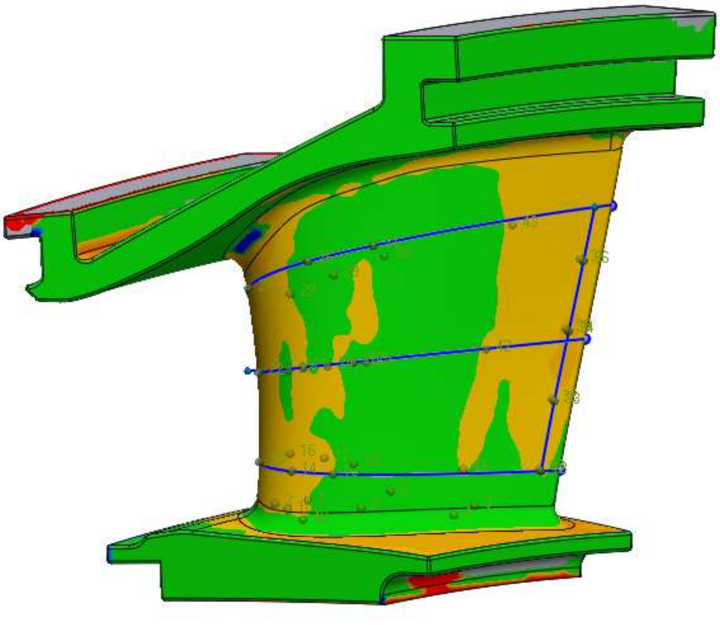
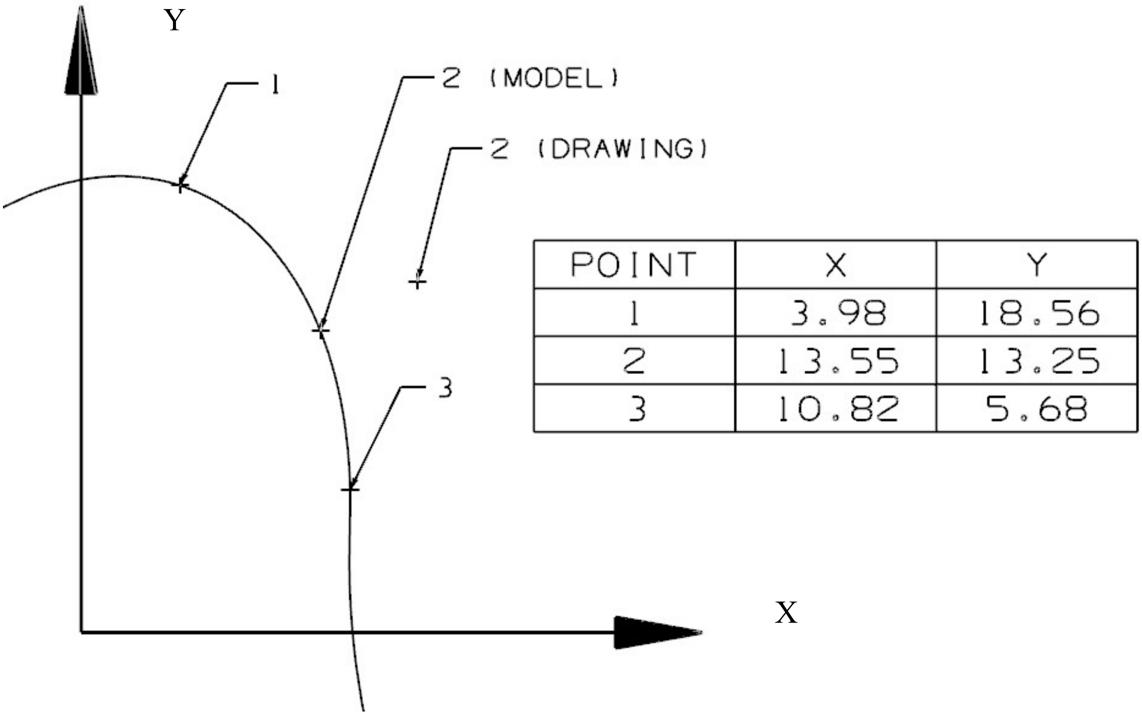


Fig.1.16. Example of a definition with additional data for inspection inside a neutral format file used for a 3D scan inspection.

1.6.2. Historical background

A traditional, but still commonly used in many companies, way of defining the manufacturing and quality requirements was to present everything in the 2D drawing or/and with 2D supporting documents like quality requirements, dimensions check protocols, areas for inspection, and many others. Datums information and datum control points positions used to be marked in a chart or a table. A significant disadvantage was that those kinds of data information were not linked to the original CAD model. It was impossible to verify whether they matched outside the original system (or outside the mother company). Manufacturing plants accumulated a wide range of evidence of cases where the drawing contained an error or a change not implemented in a CAD file or vice versa. A simple example is shown in Fig.1.17. We can have a perfect configuration with a perfect definition, but even these can be mismatched, while a CAD file will exist without direct connection to 2D or 2D will be updated without changing an original CAD source file.



POINT	X	Y
1	3.98	18.56
2	13.55	13.25
3	10.82	5.68

Fig.1.17. Point definition defined in a 2D drawing is model-independent and can lead to an error.

Another error can occur while a machine will be programmed manually based on manual or non-digitalized data. In this process, the scope for error is enormous, and these errors are challenging to identify. The process is also very time-consuming, and therefore, it is where opportunities for simplification and optimization can be easily identified.

An interesting fact can be observed when an older part is recreated from a 2D definition into a CAD system and then inspected using a 3D scan method. Such a part can exhibit a large number of deviations. During the lifecycle of a part, there were no connections between all the stages of development and production steps. The situation was comparable to a children's game “Chinese whispers”: the further from the engineering desk, the more discrepancies.

1.6.3. World trends and definitions overview

MBE – Model-Based Enterprise is a term that describes the overall strategy and vision to use a 3D model as a primary source for any data processing, specification, analysis, manufacture, use, repair, et cetera (Fig.1.18) [30]. MBE is the only source for all kinds of derivative data. That can be implemented partially (a model translated into a 2D drawing), comprehensively as a model with PMI (product manufacturing information), and ultimately (a model with PMI and the inspection data). A similar term, namely “part centric,” is also used, and it is usually connected with a data management system – PLM (Product Lifecycle Management)

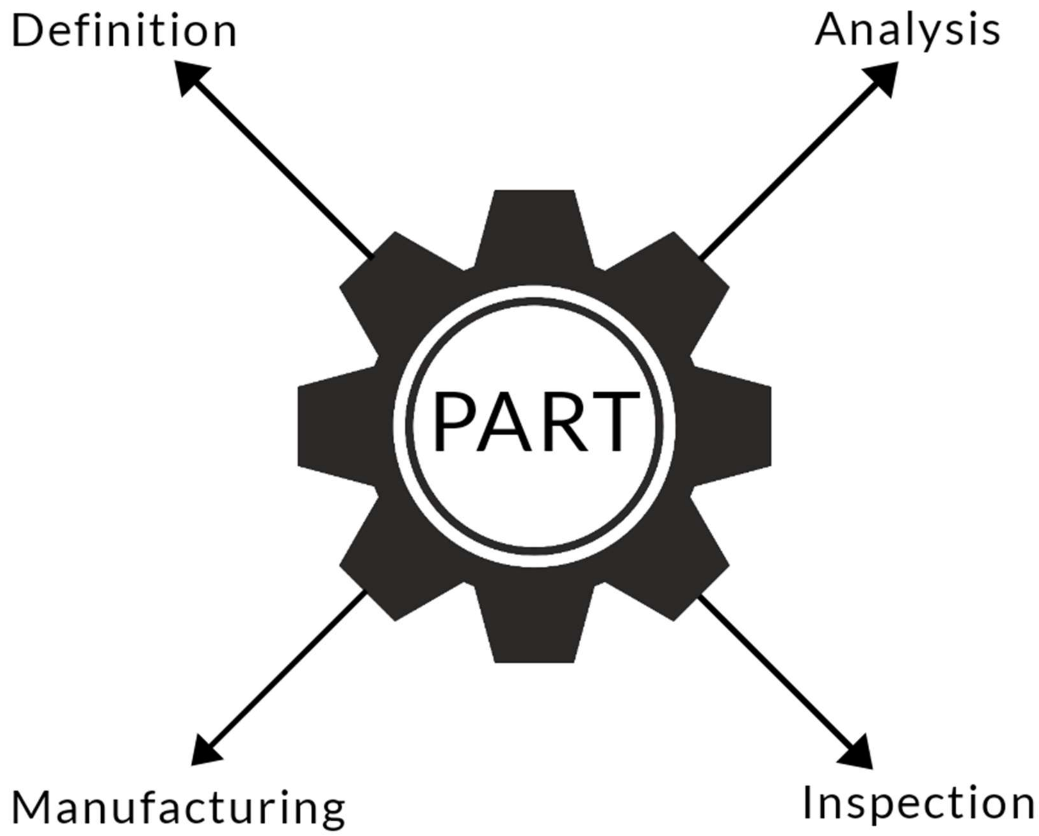


Fig.1.18. Model-Based Enterprise Vision is a one-source file philosophy.

MBD – Model-Based Definition[3] is any solution where a 3D model is used. The term is comprehensive, starting from a 2D drawing based on a model, ending with just a 3D CAD file with a digitalized definition inside, without any supporting documents.

PMI – Product and Manufacturing Information can be understood as an annotated 3D CAD model [34] that contains all the information needed to define a product, including GD&T (Geometric Dimensioning and Tolerancing) requirements [88][90]. Some visualization can be executed with 3D to PDF translation, but this derived output cannot be used for further digital operations.

1.6.4. Modern Approach

A solution for maintaining associativity and full definition can be achieved simply – as one data source for all kinds of operations and processes. That is the main "goal" for one standalone, fully defined neutral format data file. A complex set of requirements should be provided before the translation, and the file creation can be easily automated to repeat for every part.

There is a standard defining a technical aspect - ISO10303[105]**,** which will be described here from a practical perspective to add all the part lifecycle steps.

1.6.5. Neutral Formats: Most Common File Types

IGES

Historically, IGES (Initial Graphics Exchange Specification)[7][87] is the first standardized format described by the American National Standards Institute (ANSI) in 1980. It evolved from the U.S. Air Force's Integrated Computer Automated Manufacturing (ICAM) program in 1979. That is quite an old format, abandoned in 1996 (Version 5.3) after STEP was introduced. That means that the IGES format is universal and should work on all, especially older devices, but at the same time, it is limited to simple applications only. The derived output in IGES can contain solid bodies, sheets, points, and curves with the appropriate names and descriptions. IGES usually creates surfaces that can reveal gaps and missing faces. It is often not the best format for sharing accurate data, but it is still the most commonly used.

STEP

STEP[111] is a desired and worldwide supported neutral format, standardized by ISO 10303[105] (Standard for the Exchange of Product model data) in 1994.

STEP format has many variations, but commonly used in CAD systems are:

AP203 – Configuration controlled 3D specifications of mechanical parts and assemblies– mainly used for 3D specification and product structure. A subset of AP214 but more widely used.

AP214 – Core data for automotive mechanical specification processes

AP242 – Managed model-based 3D engineering - engineered to cover PMI definition. It is the merger of the two leading STEP application protocols, AP203 and AP214.

STL

STL (StereoLithography) is a format developed by 3D Systems [112] as a triangular representation of 3D CAD data. The external part shape is tessellated into a series of small triangles. It is generally dedicated to additive 3D printing technology and even for 3D scan data exchange - so it is not intended to transfer any traditional manufacturing or inspection data. This format should be treated as an extension of the data package, not a standalone system.

1.6.6. Other types of neutral file formats

Geometric Modeling Kernel Formats – CAD systems have modeling kernels that can also be used for file transfer to obtain the correct geometry. A disadvantage of kernels is a limited number of applications as it is not developed to transfer all the manufacturing data[114]. This solution is better when the native format cannot be used. Other CAD systems commonly have options of importing and manipulating kernel formats while maintaining the same quality (geometry fidelity with the native format).

CGM – "Computer Graphics Metafile" – a free and open kernel standard for exchanging 2D vector objects, raster images, and text. A popular format to exchange drawings between CAD systems.

Parasolid - is a kernel format owned by Siemens PLM Software. It is slightly different from STEP and IGES, as every NX release introduces a new version of transmitted files.

The Parasolid should be used with caution, as it stores only solid bodies without points, curves, and datum systems[109].

JT- is a format initially developed by Engineering Animation, Inc. and Hewlett Packard, further developed by Siemens PLM Software. It is engineered to present and exchange CAD data with PMI standards. The most significant benefit of JT is that it can be opened by free software JT2GO. It is also possible to attach 3D JT models in Microsoft Office tools such as Word or Excel files[104].

DXF, DWG – a format developed by Autodesk for data share between AutoCAD and other CAD systems[94]

Other systems like VDA-FS, PDES (Product Data Exchange Specification) have a marginal impact on the industry.

Table 1.1. Neutral Format Comparison[92]

Neutral format	**IGES**	**STEP**	**Parasolid**	**JT**	**STL**
proponents	ANSI/ASME	ISO 10303	SIEMENS PLM	SIEMENS PLM / ISO 14306	3D Print Manufacturers
file extensions	*.igs	*.stp, *.step	*.x_t	*.jt	*.stl
geometry type	precise	either or both	precise	either or both	tessellated
parts in doc	single	either	single	either	single
curves, points	**YES**	**YES**	NO	**YES**	NO
surfaces	**YES**	**YES**	**YES**	**YES**	**YES**
solids	**YES**	**YES**	**YES**	**YES**	NO
colors	**YES**	**YES**	**YES**	**YES**	NO
PMI	NO	**YES**	NO	**YES**	NO
Product Structure	NO	**YES**	NO	**YES**	NO

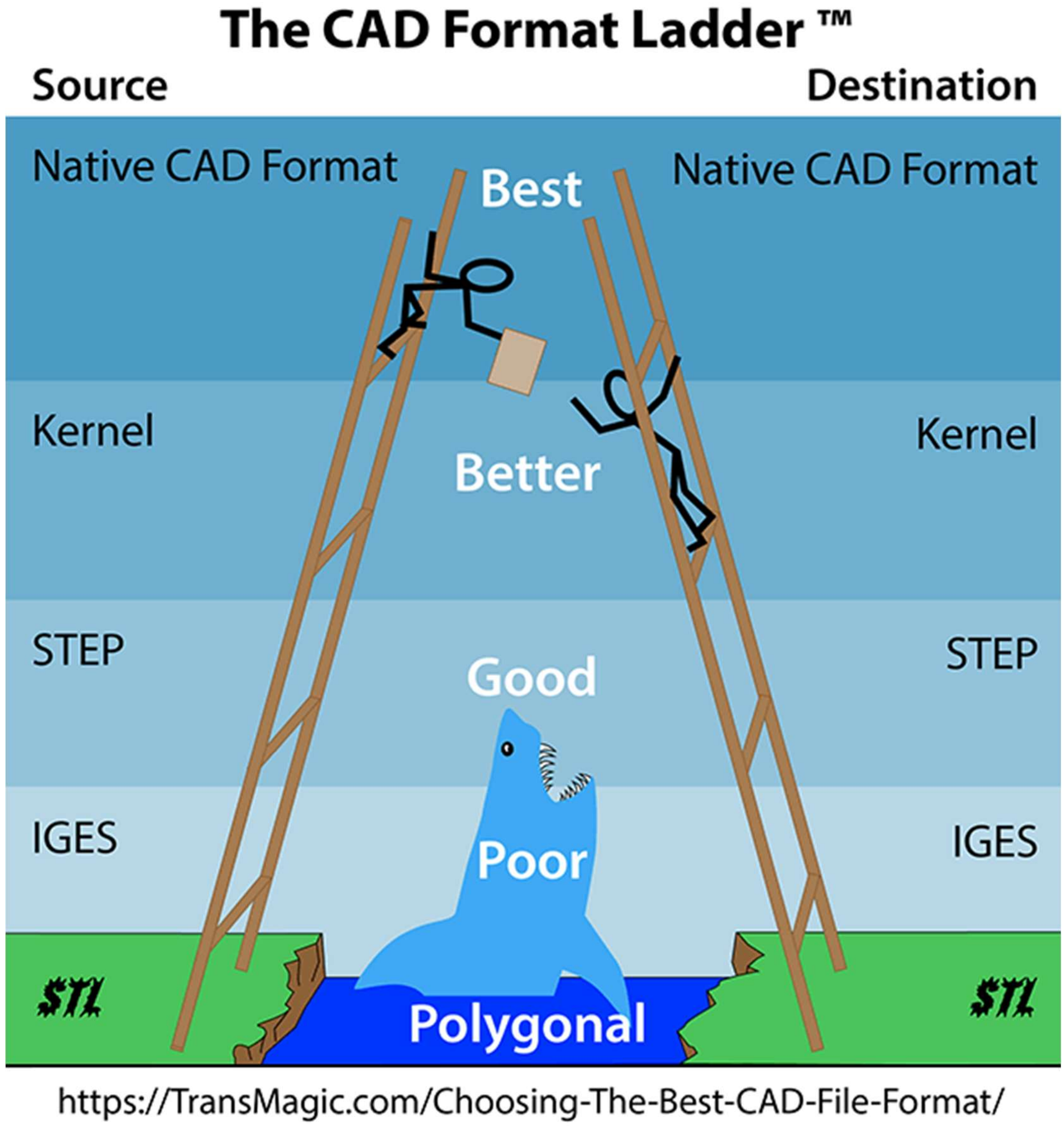


Fig.1.19. Humoristic art created by TransMagic company to visualize file-formats co-relation[93]

1.7. Traditional measurement problems

Where the process to engineer and manufacture a part is complicated, inspection is also crucial. Nowadays, the most reliable methods are the coordinate measuring machine (CMM) method and optical scan. Both methods have their limitations, so there is still a big room for improvement, and that is why we can find extensive researches in many journals[39]. CMM is faster and more precise, but a 3D scan can verify the overall shape compared to the original CAD model[35, 49]. The significant benefit of CMM is that this is more solid and has well-established rules defined in globally distributed standards [89].

Researchers typically highlight that CMM still is relatively slow, as the inspection time can vary from seconds (fast CMM scanning techniques with smaller accuracy) up to several dozens of minutes for a stationary and precise type of inspection [41]. That is why we have a big room for improvement and simplification in the aspect of mass production.

Abdullah[1] highlighted geometry discontinuities (identified problems like cracks, small holes, or varying depths), inferring that the CMM method can miss some of them during inspection (Fig.1.20). Typically, this issue is solved by other corresponding inspection methods like FPI or DPI (low-cost inspections to detect surface issues), which must be performed after casting to verify material consistency.

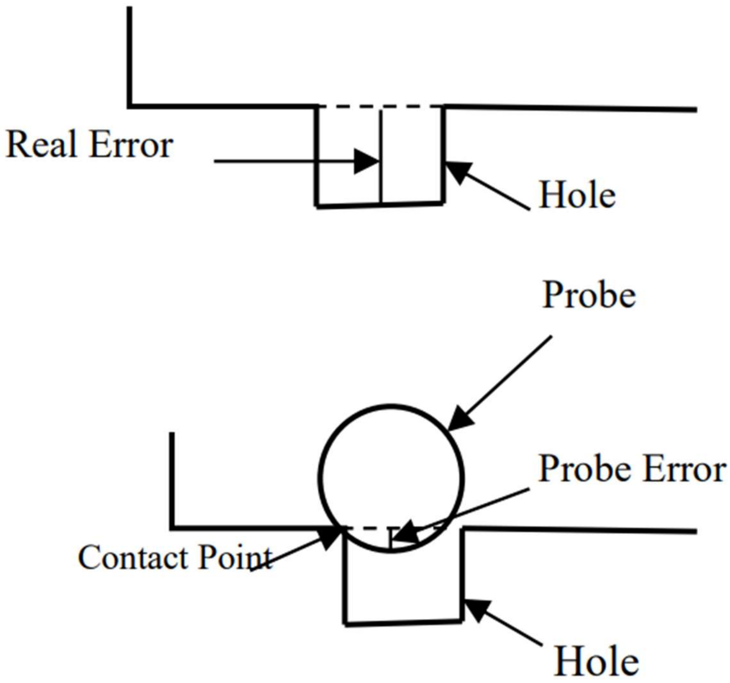


Fig.1.20. Real "small" surface issues will not be measured by CMM correctly. This kind of issue will be identified under NDT methods like FPI or DPI.[4]

In the works of Chang [16, 17] or Ristic [67], we can read many good examples of possible collisions or probe damages coming from shape variations on mass production parts. Nowadays, we have automatic tools to calculate all "worst-case scenarios" like tolerance fluctuation or part position shift on the CMM table. A critical aspect like rapid curvature change (Fig.1.21) on aero shape components needs to be adjusted "in fly" by the inspection program. Ainsworth [2] also described the importance of the additional shape variation coming from parts exceeding defined tolerances, leading to undesired probes damages. Additional space for such phenomena is called the "box of safety."

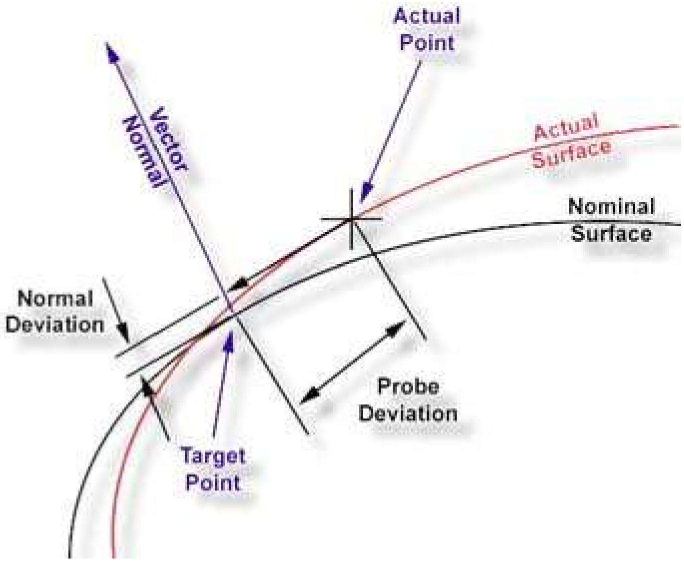


Fig.1.21. The actual surface may differ from the original CAD shape[103]

The most widely developed and most popular optimization is the path simplification process. Global researchers propose many algorithms, e.g., Mansour[54] or Rui-Song[41]. The standard and apparent aspects are to eliminate measured points to an absolute minimum to maintain the same level of accuracy. The source of such planning comes nowadays from the original CAD model, which defines a part. Another good place to highlight is that the CAD model is the primary source for all manufacturing and measurement processes[25]. That is why we need to maintain the proper translation through different machines.

Going from "curve" specific observations, researchers also focus on the whole surfaces [50, 64, 82]. Knowing the manufacturing process, we can determine areas affected by higher manufacturing fluctuations and include them in the measurement process.

While CAD origin shape must be maintained, the inspection path can be simplified and translated into more superficial mathematical representations, including approved part tolerances and "space of safety" for inspection. Weishi Li[48] proposed curve simplification based on the knots removal, whereas Hyungjun[60, 61] transferred this solution for the surfaces.

With a base CAD math knowledge, a good starting point is to define a simplified CMM path based on knot removal methods. The first action is to re-draw a curve into a more straightforward representation (C2 or even C1) and then remove up to 99% of knots, still preserving a shape to inspect within desired tolerance (Fig.1.22) [69]. Binder[9] and Cusimano[21] presented some examples of defining a curve based on the noisy point clouds.

Eck[24] also presented some practical examples used in comparison to modern CAD origin shapes.

Nowadays, many tools and algorithms are already implemented in commercial software. Hence, many things can be easily automated: probe adjustments and interchange, path planning, or even the measuring protocol[75]. Final intelligent CMM inspection needs to be verified on a particular object to prove and justify its simplification.

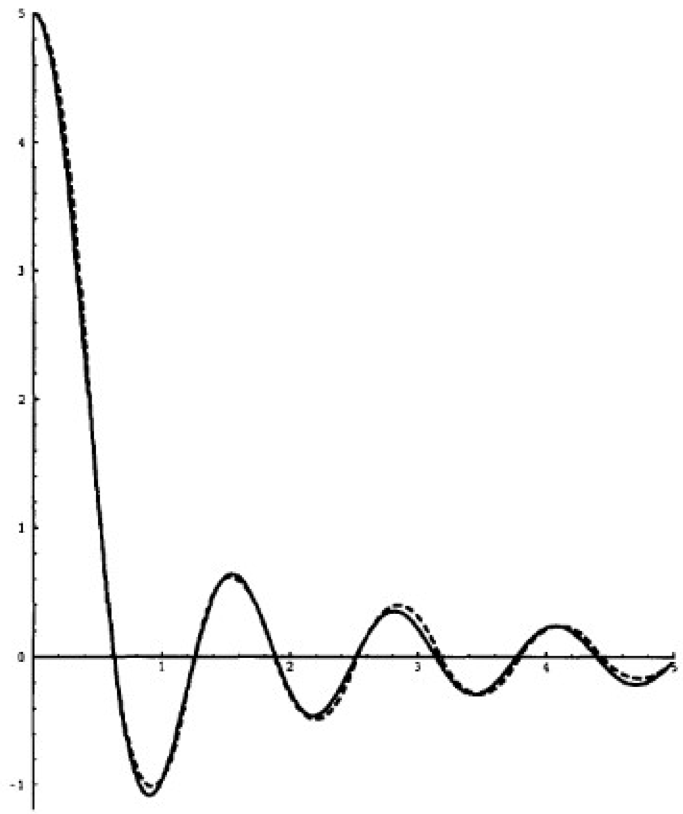


Fig.1.22. An example of the spline with 999 knots (solid line) and simplified one after removing 986 of them (dotted) [69]

1.8. 3D scanning measurement overview

Inspection for the surface or even the entire geometry shape based on optical 3D scan is the most exciting and promising method gaining more popularity each year. A 3D scanner can examine bigger geometries[22], and their potential is almost unlimited. There is a broader application than CMM as we can scan entire machines and even buildings.

Going into an opposite direction into smaller components (like the subject of this work – a turbine guide vane), we have the potential here to use both traditional CMM methods and a 3D scan. While CMM has many requirements pre-defined[89], there is still a big field to achieve similar things in the optical scan approach. Also, it cannot be neglected that many deviations may be revealed during inspection (blurs, holes, partially or incorrectly registered surfaces, or even background noise (Fig.1.23)). A detailed scan is a set of smaller, partially collected datasets that can be distorted during the transition. All of that needs to be considered during the inspection and cleaned or filtered to provide reliable results[55]. Some commercial software like Geomagic WRAP[97] could automatically solve many of these issues. Precise measurements on a small surface are still problematic even for modern algorithms, and in many scenarios, manual interpretation is still needed at the end.

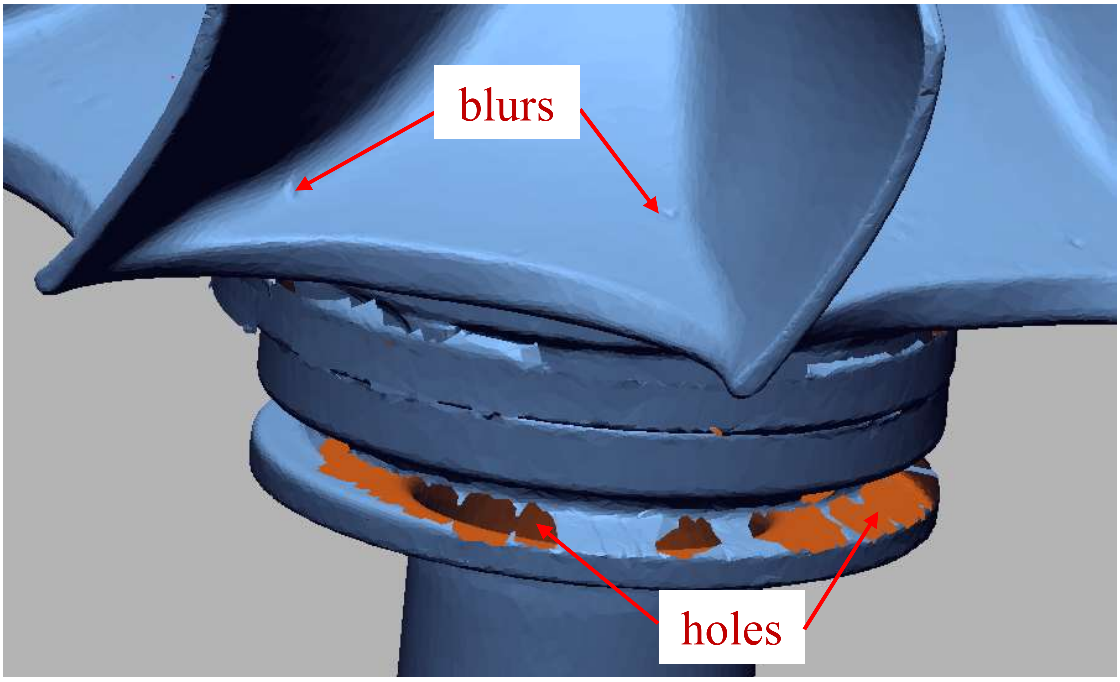


Fig.1.23. Blurs and holes are typical imperfections of 3D scans [98].

That is also why CMM is still a more trustworthy type of inspection, and that is why the 3D scan is the favorite research topic nowadays, with a mission to make it interchangeable with CMM for the near future.

Many algorithms can be found in the literature. Fan[28] proposed a method to extract a curve profile from a raw point cloud. Lingxiao[46] introduced an approach to fit primitives (small and straightforward geometries like planes, circles, cylinders, et cetera). Liu[51] did more extensive work to define more complicated shapes. Yang[81] improved algorithms of Zhong[85] or Pauly[62] to find pre-defined features on large volume scans. Such an approach can be used in even more complex conditions proposed by Fehr[29], who made similar extraction from a 2D photo. Hackel[33] used mentioned methods to reconstruct the contours of buildings.

These examples show how powerful modern tools are and what to expect in the following commercial software updates. The trend is to automate processes as feasible and eliminate manual works or even human engagement from the entire process [79].

Industrial trends are being set by Geomagic Design X[96] or Geomagic Wrap[97] software - commercial reverse engineering tools. Geomagic Control X [95] or a GOM Inspect[99] can be used for the final inspection.

1.8.1. Computing mesh data

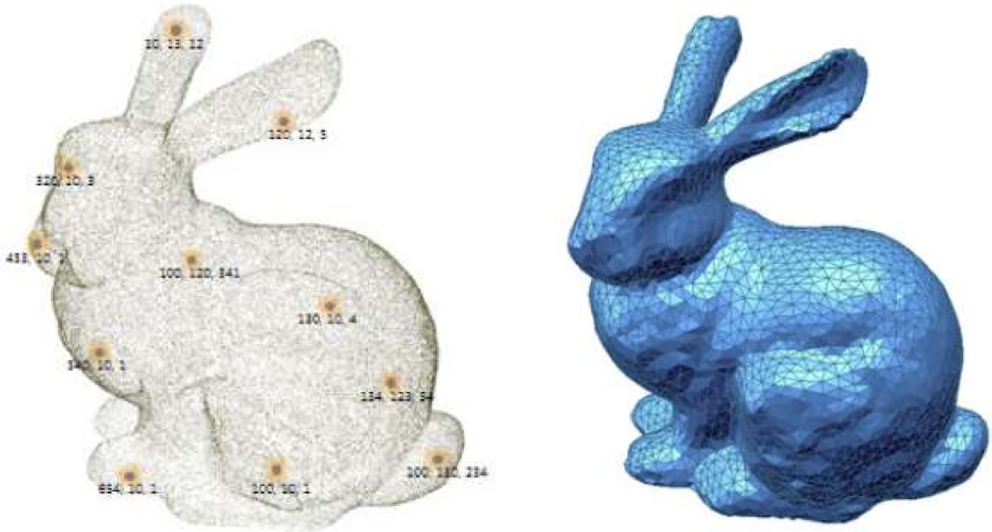


Fig.1.24. Point cloud on the left and triangulated mesh surface on the right [98]

3D scan in an initial phase is just a big cloud of points (Fig.1.24) with or without the vector how it was captured by the scanning machine (Fig.1.25). Point clouds can be visualized on PC, but any 3D application does not use that form. This dataset needs to be converted into a mesh (polyhedron-based 3D digital data) – triangulated shape. [112].

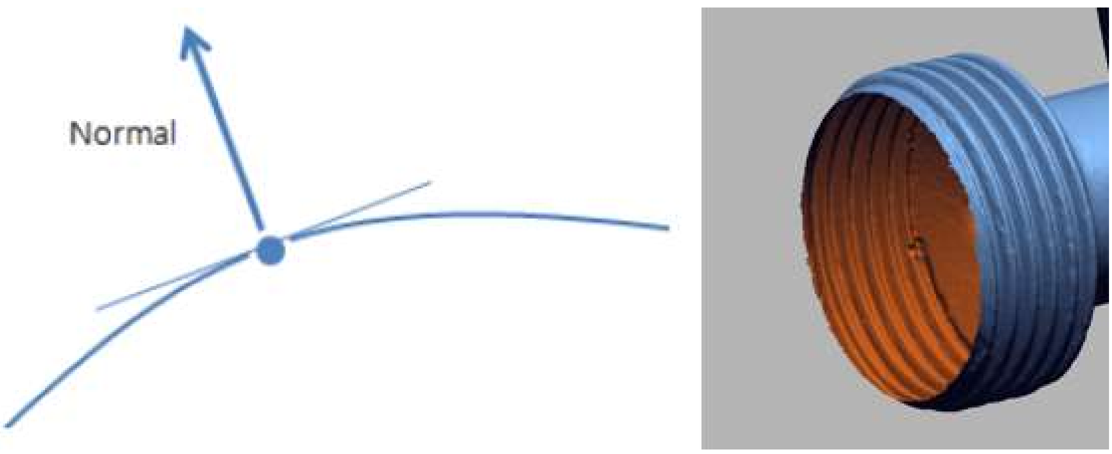


Fig.1.25. Additional normal vector helps to visualize the entire model in the computer system. Blue color for external surface and orange for internal [98]

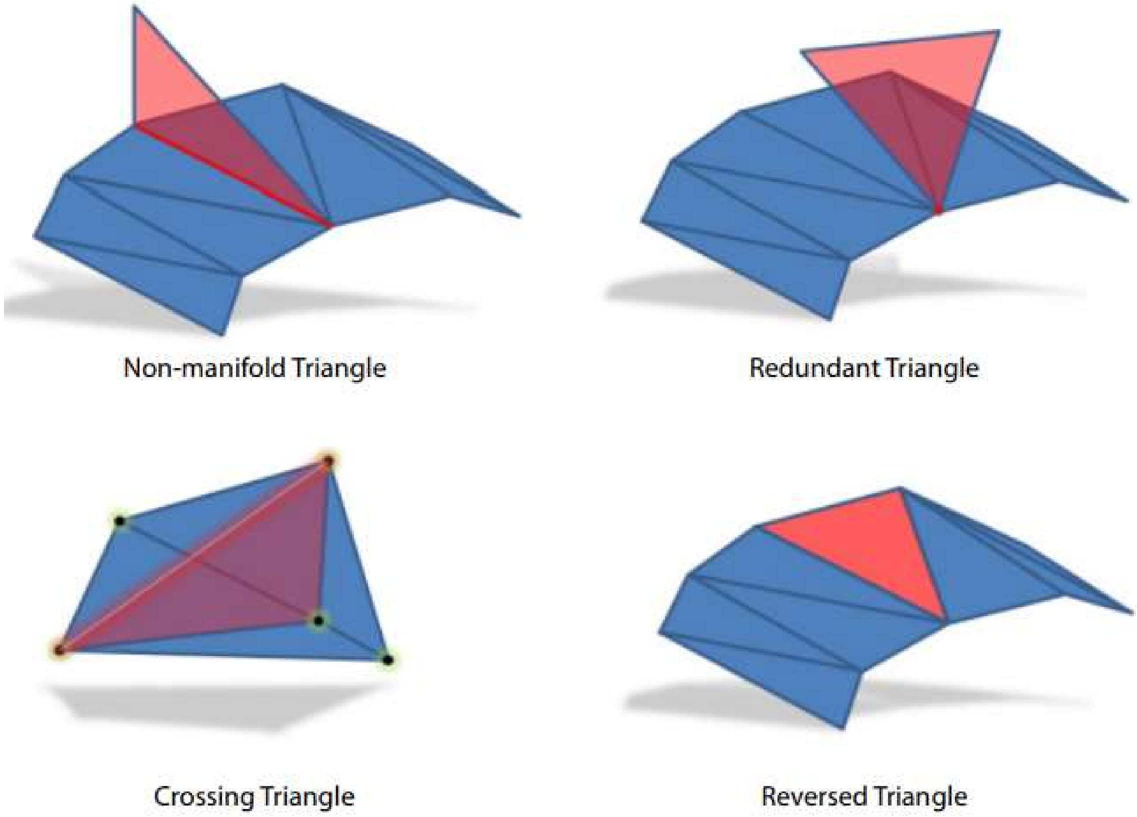


Fig.1.26. Examples of mesh flaws[98]

Such mesh needs to be improved by removing non-manifolds, redundant triangles, spikes, et cetera. (Fig.1.26) [15]. After that, a 3D mesh can be then decomposed to recognize model contours[45]. Such preparation allows performing a 3D analysis with the use of a 3D CAD model as a reference.

The group of things that are not so obvious are the differences allowed by manufacturing processes but not adapted into a 3D CAD origin model. 3D scan inspection could be performed only with CAD reference to calculate all process deviations. Again, a proper translation of the original digital data has the utmost importance here. We count here blends and chamfers introduced to remove sharp edges. Other examples are casting gate leftovers, designated to be removed later or even by a different manufacturer specialized in machining operations.

2. Thesis and objectives

2.1. Motivation and general objectives

There is a long way from the first point in the CAD system to the fully developed, manufactured, and assembled part. Much intense research is available for the main steps of part development, as highlighted in the previous chapter. Many problems and issues are already solved and introduced in the industry. Many of them are still under extensive researches for continuous improvement both for speed and accuracy.

Tools available in the industry have one common point: they are not developed to engineer a specific component; they are developed to engineer any possible component and any idea that can be challenging for manufacturing or even impossible (yet) to produce.

Part-specific requirements can be set beyond standard tools and processes to impact industrial competitiveness and industry share significantly. Some of them are the main goal for patents; some are the internal secrets of a specific company.

Those are the aspects where we still have a big field for extensive researches like:

- FEM deformation which is not intended to be a production shape
- Part shape continuities which can be more sophisticated than the typical CAD capabilities
- CAD data exchange not to lose the original shape condition
- The part inspection set with correlation to a working condition or mechanical objectives
- Precise part inspection on a small surface by optical scanning
- Inspection methods interchangeabilities (touch technology and optical scan)

2.2. Thesis

The innovativeness of the work is to focus on the unexplored areas of the part development. Some unobvious mid-processes (steps) are highlighted, which are not well described yet in the public literature (Fig.2.1). The turbine guide vane is an excellent example of a part that is hard to develop and manufacture concerning the main shape of the deformed working condition.

The main aspects covered under this work are:

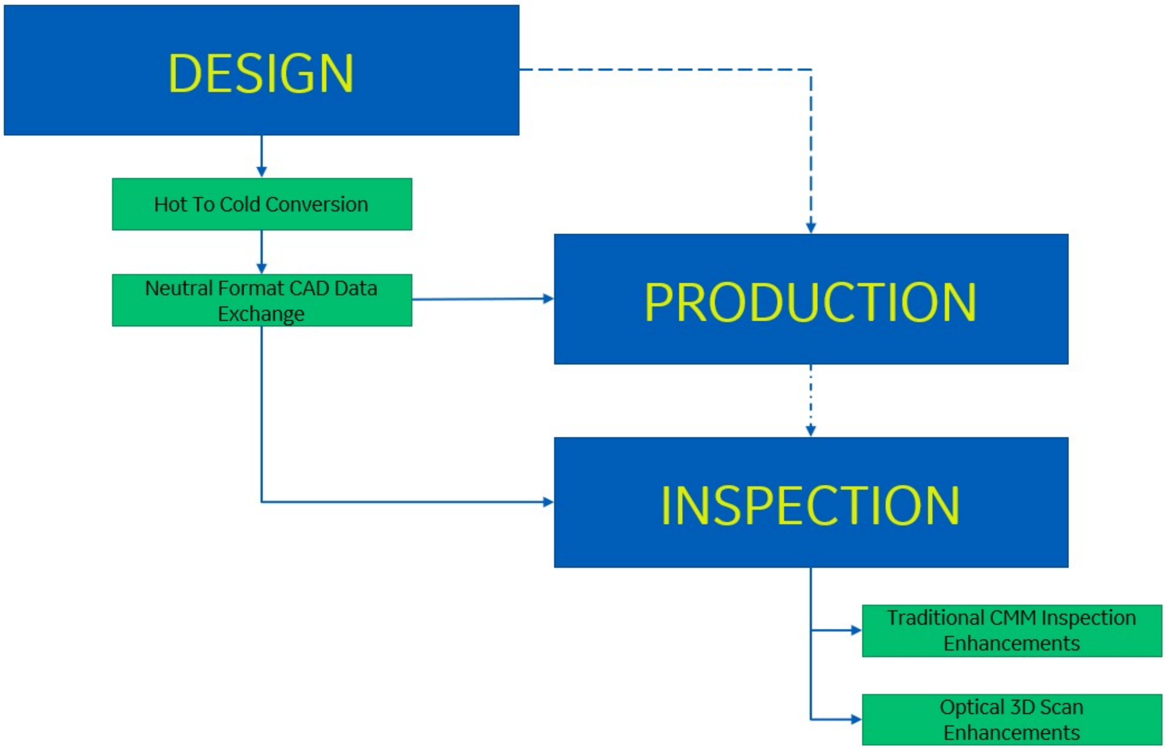


Fig.2.1. Mid-steps examples for the turbine guide vane part development.

- **A hot to cold deformation matrix:** Typical working condition for turbine guide vane component exceeds 1000 C degrees. Thermal deformation can be visible to the naked eye, so a part engineered to work in a high-temperature range needs to be deformed into a cold production shape. This translation accuracy could be improved with modern optimization tools and algorithms.
- **Trustworthy CAD data exchange process:** Due to different file formats used in the production and inspection machines, uncontrolled data translation could lose manufacturing details or distort the original part shape. Digital data packages should not be created as a copy-paste of the previous pre-CAD techniques. Some aspects could even be eliminated if human interpretation is not profitable. A reliable method for proper geometry transfer with manufacturing and inspection details could be established.
- **Traditional (touch technology – CMM) part inspection simplification:** A reliable and simplified CMM inspection method could be established based on CAD geometry and part mechanical objectives. Some aspects could be simplified or even eliminated based on other inspection methods' capabilities.
- **Modern optical inspection enhancements**: The optical scanning method still has lower accuracy but uses more points in inspection than CMM. While CMM has a

strictly defined safety border for measured areas, the optical inspection method does not recognize part contours correctly. A method to increase small surfaces measurement accuracy is possible to develop. Interchangeability of touch and scanning technologies is achievable.

All these aspects lead to a general thesis description:

Accuracy of a Turbine Guide Vane geometry engineering can be increased based on the correct digital data translation and proper shape optimization.

3. Prototyping – hot to cold conversion matrix

As already mentioned in the introduction, a proper prediction of a part behavior is crucial to obtain assumed conditions and achieve desired performance. A first development translation begins on a hot to cold transformation. To perform a proper process, there is a need to define and describe all significant thermal behaviors and constraints observed on all typical thermal analyses.

3.1. Thermal assumptions

3.1.1. Engineering constraints

3.1.1.1. Bulk temperature

Overall, temperature map distribution is a complex topic and cannot be perfectly measured on an original part. We can inspect local max temperatures by thermo-crystals, but this method requires disassembly from the machine and is not designated for the entire component's life. We can rely on a well-performed CAE simulation to predict areas with higher and smaller temperatures (the cooling aspect is one of the essential assumptions). That will bring a significant aspect, as we cannot define the actual temperature on every square millimeter. Bulk temperature for a 2D section defining CAD sweep shape can be introduced here as the engineering constraints.

3.1.1.2. Mechanical objectives

A fully defined CAD needs to be updated with all mechanical features for long-life work under aggressive conditions. Features that can be highlighted as an example of additional engineering constraints:

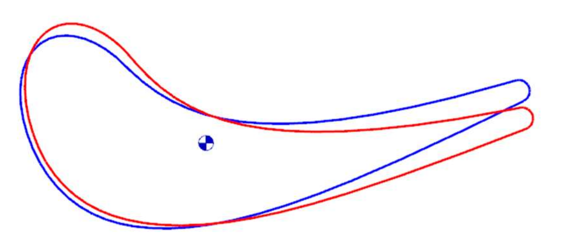
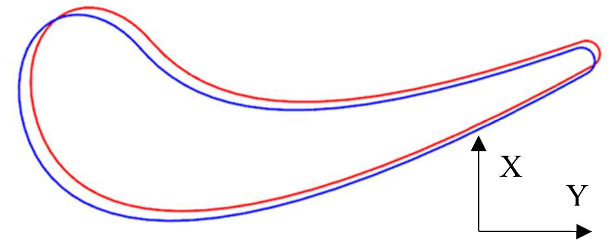
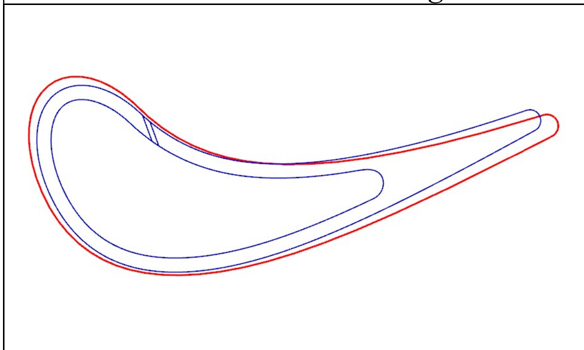
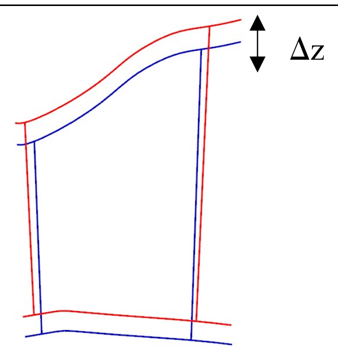
- massive blends between airfoil and platforms (defined by other analysis, an iterative loop can also be implemented here to play between blend irregular shape and stress concentration)
- internal cooling core cavity – stable wall thickness
- cooling holes
- coating

- all other standard machining and tooling sizes, which shall be maintained in cold shape

3.1.2. Engineering variables

A 3D CAD model prepared to adapt during engineering changes and reverse hot to cold transformation must also include some typical variables. The following list has been established based on four years of experience from ~50 independent analyses made by the author. All common meaningful behaviors have been presented below:

Table 3.1. Engineering Variables: red lines – outer hot aero shape, blue lines – cold section of a part.

<table>
<tr><td>Variable: 2d section twist.</td><td>Variable: X and Y 2D Movement.</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td>Variable: 2d shrinkage.</td><td>Variable: vertical movement.</td></tr>
<tr><td></td><td>
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- ***2D Twist -*** This deformation can be considered on a specific 2d section. Every 2d section has the potential to twist. The center of gravity of the section will be defined to calculate angular twists.
- ***XY Movement -*** After thermal translation, there will also be a 2D position movement for the center of gravity. Adjustments will be needed separately for the X- and Y-axis positions.
- ***2D shrinkage parameter -*** Every 2d section will be slightly smaller in a cold position, so this variable will scale down the original section to adjust thermal shrinkage. A total area ratio will give a shrinkage factor – S.
- ***Vertical extension -*** All input curves will change their radial (vertical) position, so their movement shall be included as a variable Δz.

3.2. Proposed Methodology

3.2.1. A CAD-CAE loop

As a turbine flow performance is calculated in a hot working condition, there is a need to introduce a loop in the process. The hot aero shape needs to be translated into a single component modeled in an associative (changeable) mode in CAD, equipped with all other (standard/cold) features like core, cooling holes, and other features affecting the shape of thermal deformation. The 3D model will use variables to change engineering objectives during a FEM iterative method cycle proposed by the author (Fig.3.1). A final "cold" 3D model shall match thermal deformation to the primary, original aero shape in "hot" condition and machine position (Fig.3.2 and Fig.3.3).

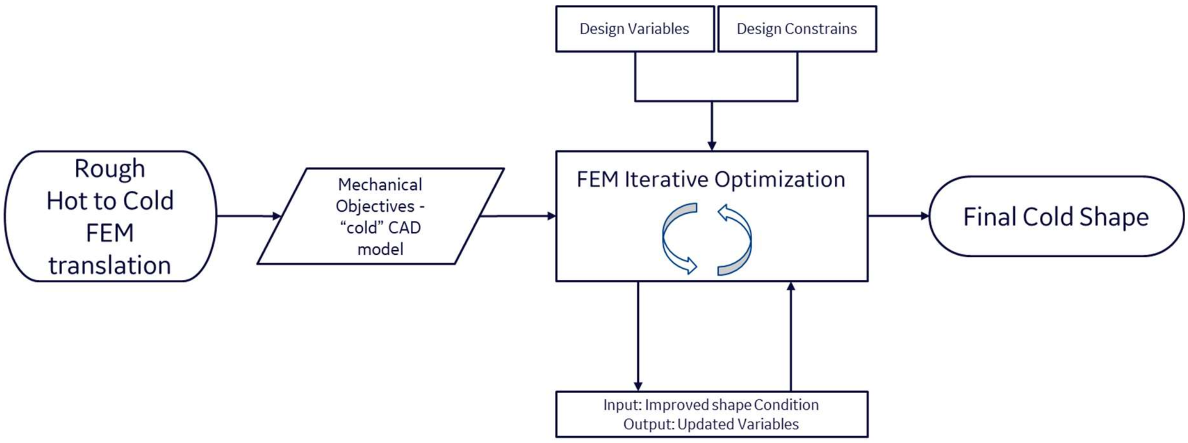


Fig.3.1. An iterative loop for the prototyping cycle.

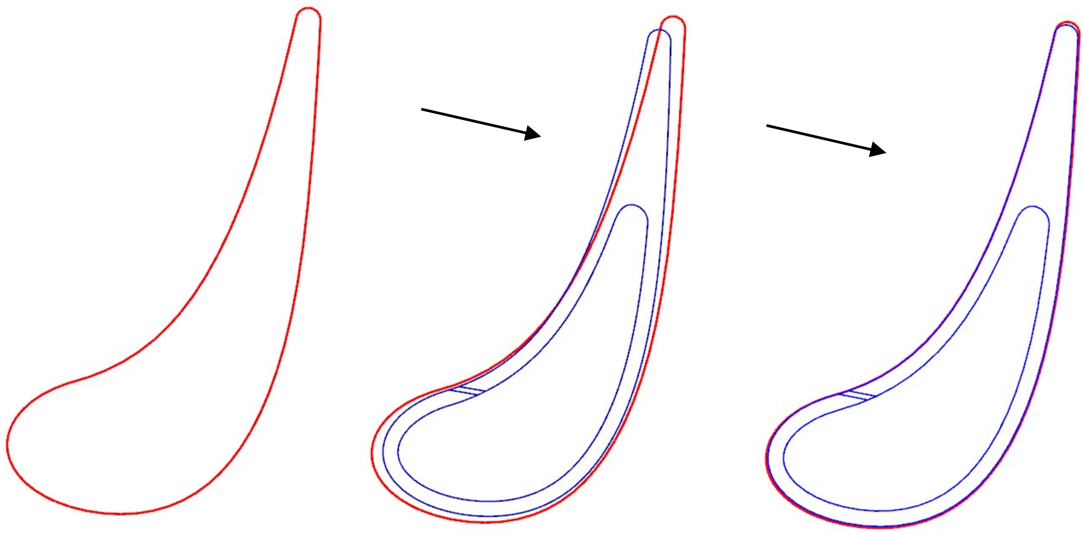


Fig.3.2. An example of 2D airfoil section process loop: A) Hot external aero shape (red), B) Cold scaled shape with engineering constraints and variables C) FEM iteration to utilize engineering variables to match original input shape in hot condition.

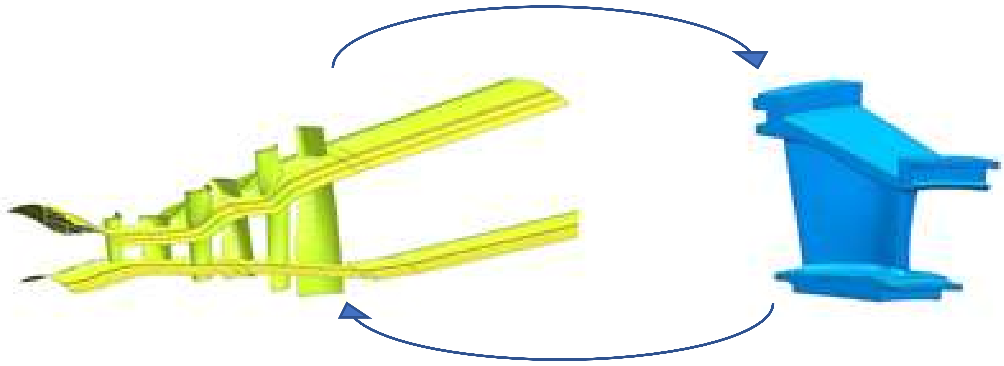


Fig.3.3. A process loop example. Aero shape without mechanical features and a preliminary CAD model.

An iterative loop proposed and defined by the author is needed because we have given a "hot" external shape with "cold" production features with constraints standardized for manufacturing conditions. An entire loop will go from hot initial shape, collecting cold details and checking with hot shape again. When a match is achieved, simultaneously, a "cold" shape will be confirmed for manufacture.

A detailed loop for iterative solver:

- Step 1: A rough hot to cold translation based on aero shape and thermal environment inputs (no mechanical features) from a big aero model with all turbine flow maps.
- Step 2: Initial engineering variables calculation (shrinkage, twist, 2D movement et cetera)
- Step 3: Preliminary CAD model with all details
- Step 4: Addition of engineering variables and constraints (core, cooling features, stress reduction blends et cetera)
- Step 5: Iterative loop with optimization algorithms, the configuration will be adjusted to match original aero shape condition
- Result: Final CAD production model
- Steps 3-5 need to be repeated as many times as the configuration changes during the prototyping loop.

3.2.2. Optimization trials – math algorithms

When a 3D model is ready, there is a time to perform a high-quality mesh with all critical features. A solver needs to play with all variables to match the original shape. Every adjustment needs a mesh update. Algorithms available for shape optimization can be divided into two groups: local and global. Local algorithms are better for finding precise answers where we already have defined borders for the desired solution. Global algorithms are better for a rough solution with an extensive range of data, looking for significant variations with more than one available solution. In our case, local algorithms will be much more valid as we are looking only for relatively minor adjustments. Initial values for variables will be obtained from rough hot to cold translation, so we are already set within a small range of possible shape adjustments.

In this work, two algorithms were used for comparison - Conjugate Gradient algorithm and Powell algorithm:

- **Powell algorithm**[77]– This algorithm has been proposed by Michael J. D. Powell[65]. This method is not using derivatives and is fast and helpful for calculating the local minimum of a function. The algorithm goes through all variables until the closest value is found.
- **Conjugate Gradient**[58] – this method was mainly developed by Magnus Hestenes and Eduard Stiefel[74]. This solution uses derivatives and is faster for mathematical forms.

The author tested those two algorithms for CAD shape optimization based on given constraints and variables. The authors, inside their official publications, well-described these algorithms.

3.3. Results

3.3.1. Pre-process validation

Two components have been analyzed in this work to calculate the difference between engineering steps and assess a process risk. First – a “hot” model without any internal cavities or cooling features has been deformed into a “cold” shape condition. A final CAD model has been created based on that “cold” shape, adding internal core and cooling holes. Then a “cold” to “hot” analysis has been performed to compare a difference with the original “hot” base shape input—all details according to Table 3.1. As a simplification for this work, the only thermal impact is covered, and external working pressure is neglected/simplified to no impact (no stress solution).

Table 3.1. Input Parameters for thermal deformations

Material	α [10(-6)/°C]	T[°C] initial [hot]	T [°C] cold	ΔT [°C]
INCO718	14.4	1000	20	980

There is a noticeable difference in shape position after analysis, up to 0,475 mm, as presented in Fig 3.4. That is too much to accept, and it is a starting point for process optimization. The final model needs adjustments to match a given shape in a hot condition.

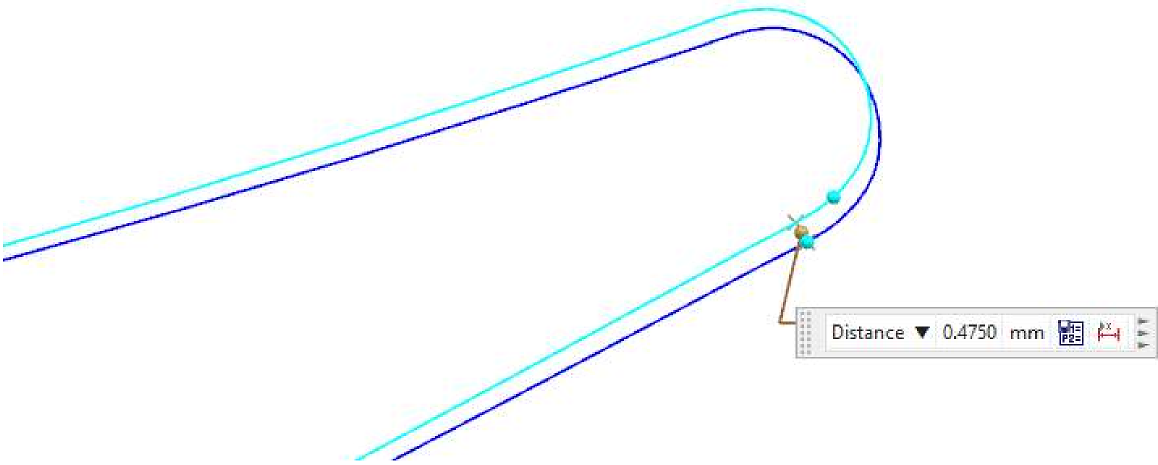


Fig.3.4. Trailing edge validation: from a hot external shape to add details on cold deformed shape and back into hot condition shape for comparison.

3.3.2. Main process loop for a fully defined component

A first rough FEM "hot" to "cold" analysis can be optionally omitted as well-known simple formulas can easily calculate rough input parameters. Untwist, and x/y movement will not be significant so that initial values can be set to 0.

- Thermal displacement:

$$\Delta z = (zo - z) * \alpha * \Delta T \tag{3.1}$$

- Shrinkage:

$$S = 1/(1 + (\alpha * \Delta T)) \tag{3.2}$$

Table 3.2. Initial values from rough hot to cold scaling based on simple formulas

Section	**HOT z-cut [mm]**	**Δz [mm]**	**Untwist θ [°]**	**Shrinkage-factor S**	**ΔX [mm]**	**ΔY [mm]**
1	**670**	1.12	0*	0.986	0*	0*
2	**635**	1.62	0*	0.986	0*	0*
3	**600**	2.11	0*	0.986	0*	0*

**initial values set to 0 to simplify input data calculations*

As proposed in this work, an entire CAD-CAE-CAD loop has been initiated with a changeable and fully detailed CAD model prepared by the author with all initial values. Process deformation ran "in fly" until the CAD model approached a close similarity to an initial shape boundary (for a FEM deformation after the last analysis). These variables play a loop on the three sections independently, as defined in Fig.3.5. A CAD model has been automatically updating each turn with the mesh update accordingly. This method has been performed two times to verify two algorithms in practice. Results are presented in Charts 1-10; values to compare are presented in Table 3.3 and Table 3.4.

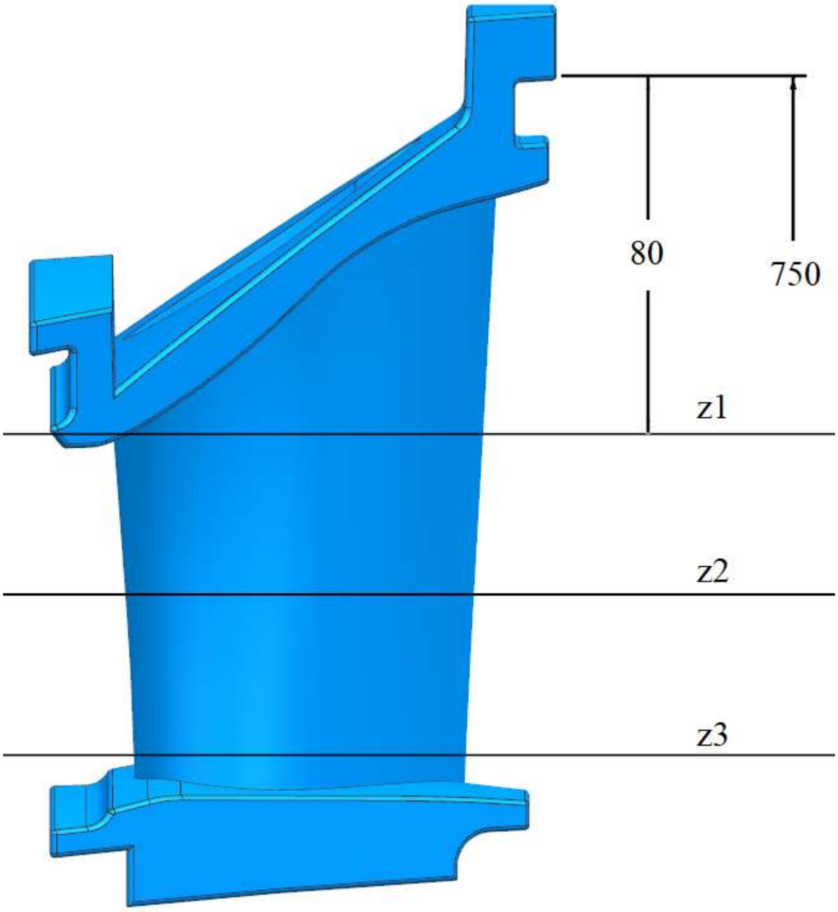
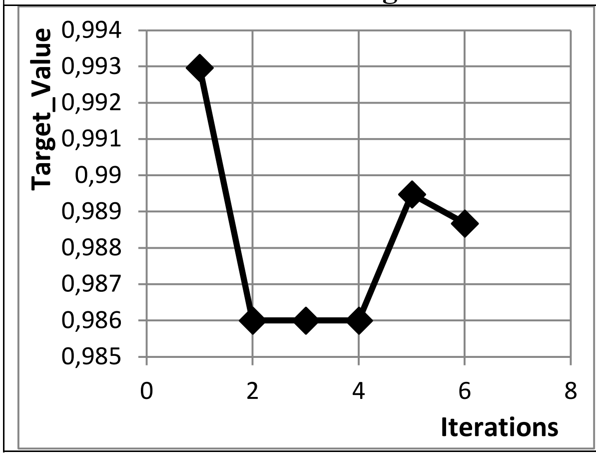
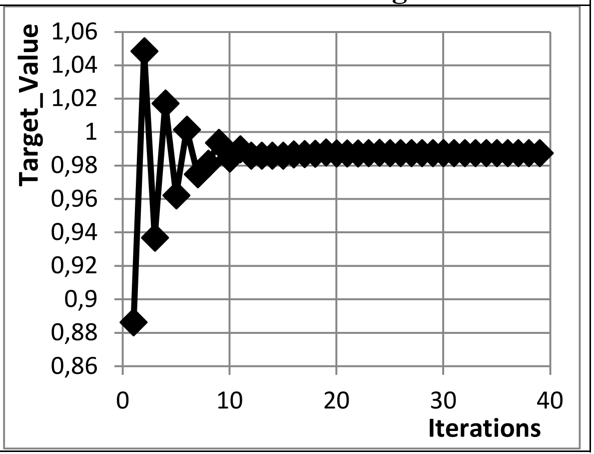


Fig.3.5. Section positions for an iterative loop [mm].

Charts 3.1-10: Iterated values for final vane shape (section z2)

Powell	**Conjugate Gradient**
1. shrinkage	**1. shrinkage**
	

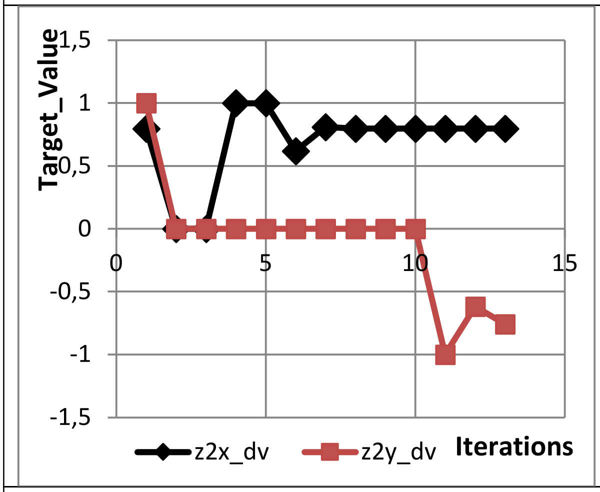
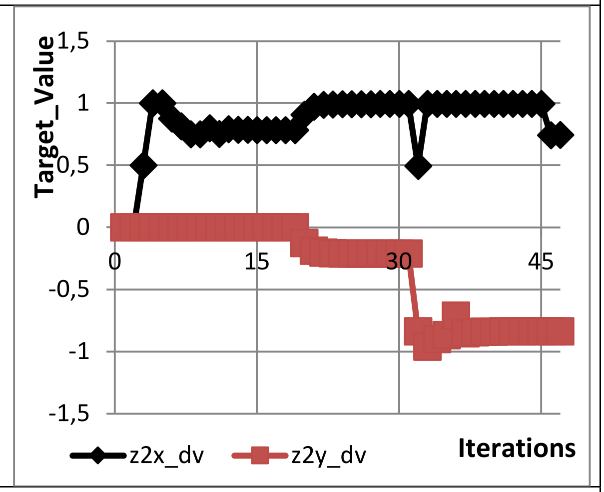
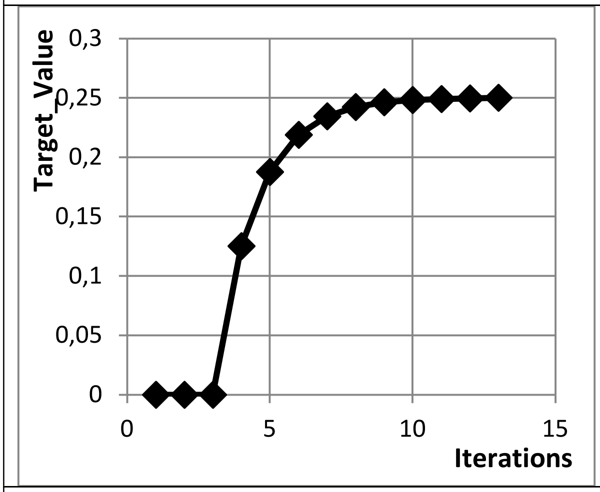
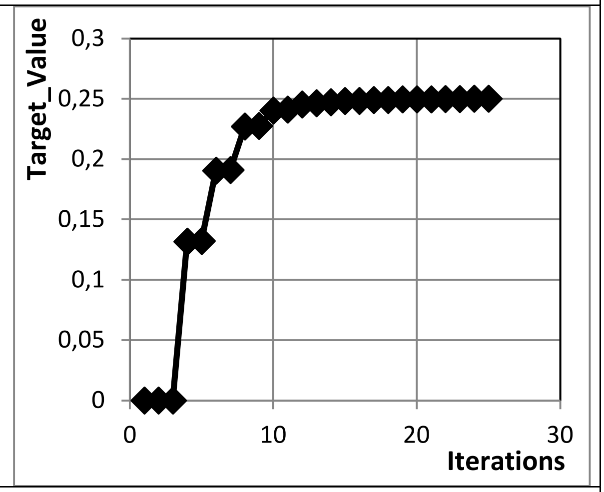
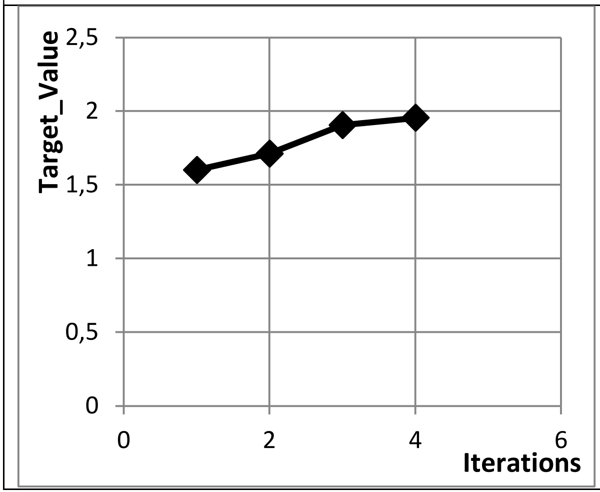
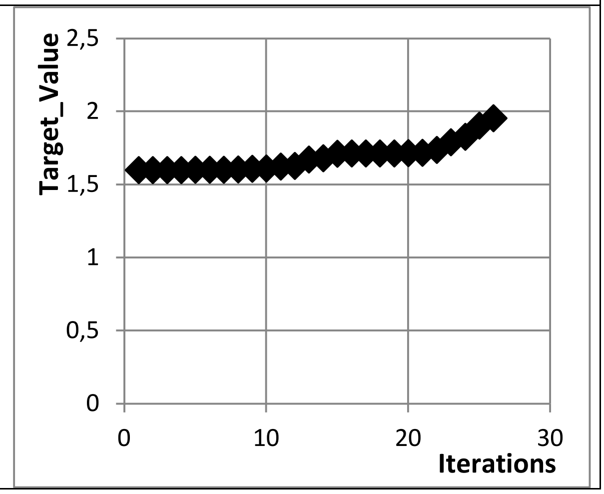
2. X and Y 2D Movement	2. X and Y 2D Movement
	
3. Untwist	**3. Untwist**
	
4. Vertical extension	**4. Vertical extension**
	

Table 3.3. Final Adjustments - Powell

Section	HOT z-cut [mm]	Δz [mm]	Untwist θ [°]	Shrinkage - S	ΔX [mm]	ΔY [mm]	Iterations
1	**670**	1.271	0.351	0.986	0.373	-0.352	56
2	**635**	1.954	0.250	0.989	0.797	-0.760	51
3	**600**	2.510	0.252	0.988	1.338	-1.062	60

Table 3.4. Final Adjustments - Conjugate Gradient

Section	HOT z-cut [mm]	Δz [mm]	Untwist θ [°]	Shrinkage - S	ΔX [mm]	ΔY [mm]	Iterations
1	**670**	1.269	0.351	0.987	0.374	-0.351	159
2	**635**	1.953	0.250	0.989	0.797	-0.759	153
3	**600**	2.509	0.243	0.988	1.341	-1.058	163

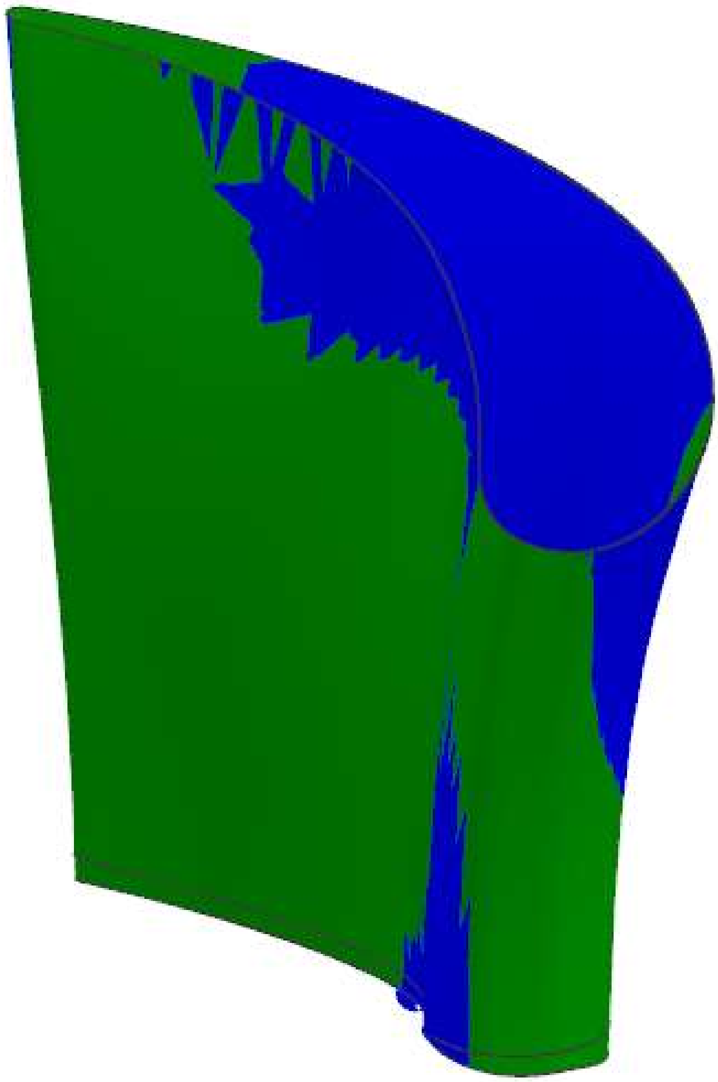


Fig.3.6. Overlay of the cold shapes based on Powell and Conjugate Gradient deformation loop.

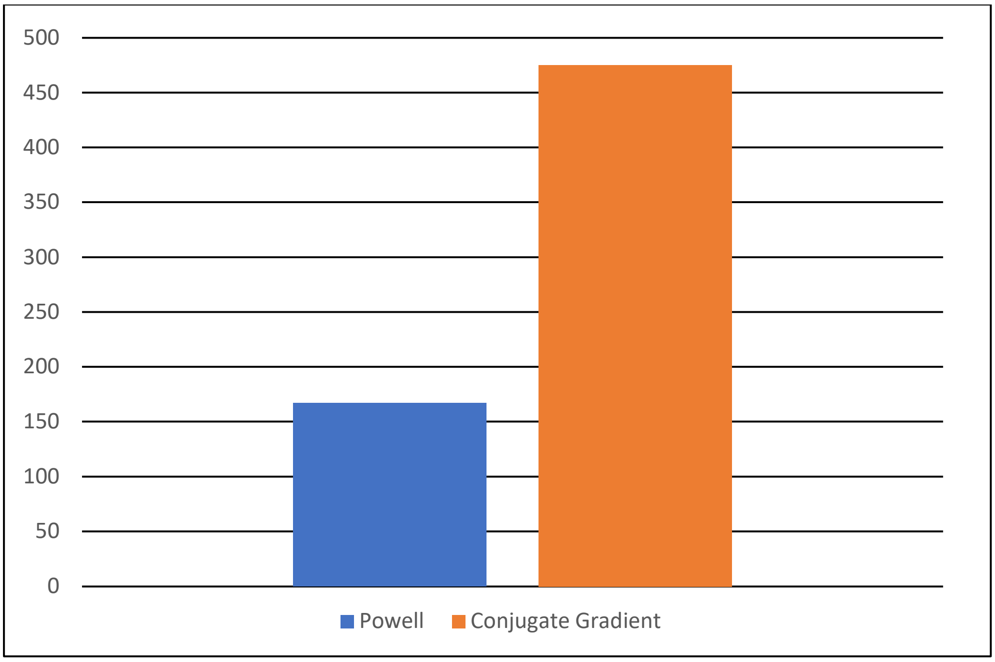


Fig.3.7. Number of iterations for Powell and Conjugate Gradient

Powell algorithm is faster and more stable to operate on an extensive set of data(Fig.3.7). Conjugate Gradient tends to take more significant changes initially and minimal adjustments at the end, so there are usually more iterations (Charts 3.1-10). Both solutions are “fast enough” to omit this criterion from consideration, as both solutions need only milliseconds to adjust variables. Powell needs a smaller number of iteration so that the FEM loop will be much faster. The time needed for a single mesh update and calculation can vary depending on the machine. The computer used for this work preparation needs around 2 minutes for every step in the loop[20]. It looks like that non-derivative Powell method is universal for CAD-CAE purposes. Conjugate Gradient could be more precise, but there will be no manufacturing benefits from a practical perspective, as the last steps are performed with tiny adjustments. Results for both algorithms are almost the same, proving that iterative thermal scaling methods are reliable (Table 3.3 and Table 3.4) – the difference is on the three decimal places that have no significant meaning.

3.3.3. End loop validation

As stated in the introduction, the shape of the FEM deformed model is not intended to be a production shape. The cold 2D section for production is a derivative from the initial 2D hot section. The initial hot shape can be compared to a deformed shape based on a point cloud obtained from FEM geometry (CAD Model deformed to external nodes from FEM calculations). Based on this, there is a possibility to verify each step of the loop. A method similar to the documented CMM part inspection[39] was used for verification. The distance between 24 representative points from FEM deformation to the CAD hot spline has been measured. Results are presented in Fig.3.8 and Fig.3.9. A very nice improvement from the initial error calculated in the previous chapter – up to 0.475mm - between the simplified and fully defined CAD/FEM model has been observed. Final adjustment received shape error up to 10 times smaller with a value around 0.05mm what is a satisfactory result from an engineering perspective and assures reliability for production and working conditions. It has a significant meaning for part development, especially where the throat value is crucial to control[53]. Pre-process validation scaling is a shape with different twist angles. That is why we can observe a local match and significant difference in other areas (Table 3.1 – 2D twist).

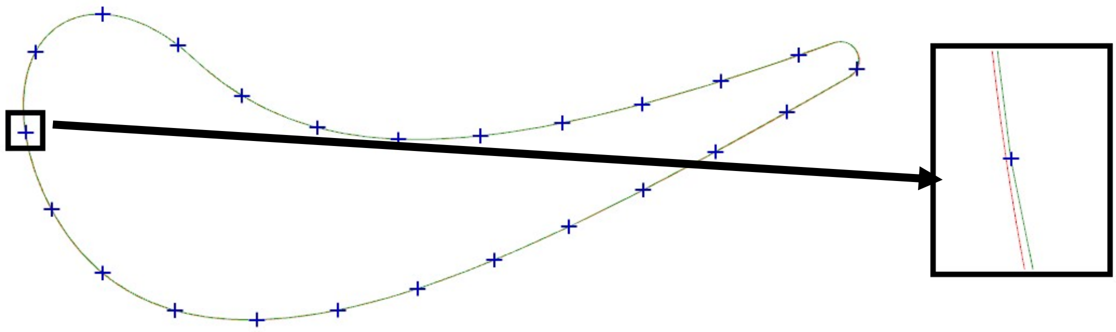


Fig.3.8. Twenty-four representative points overlayed with on the original - initial hot CAD section.

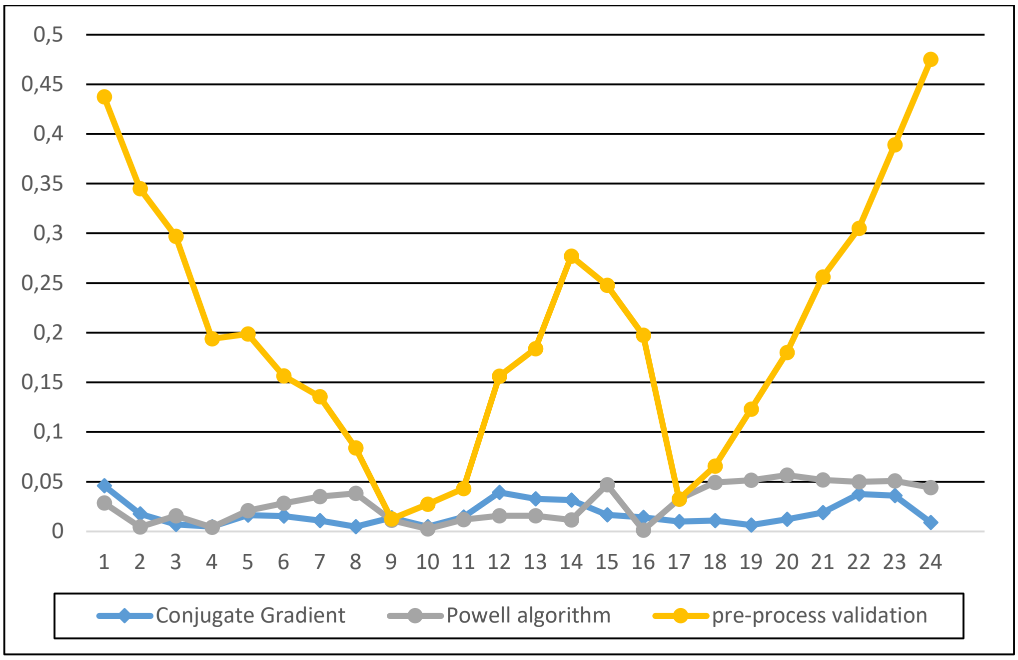


Fig.3.9. Error comparison for a hot to cold translation with comparison to a pre-process validation (Section 3.3.1.)

3.4. Discussion

Thermal deformation is a crucial brunch for prototyping with wide scaling objectives that need to be included in the process loop. The prototyping cycle is very complex, as there are many iterations within months of work to cover all mechanical requirements and changes.

A loop presented in this work aims to ensure a correct part shape, as the translation shall not be performed once, in the beginning, but continuously through the whole prototyping cycle.

Final component production is expensive, counted in thousands of dollars. Every objective change is relatively cheap on the engineering desk, while costs increase dramatically like a snowball through the part lifecycle.

Many areas are not covered in detail within this example, so there is a vast area for a similar publication for other researchers. Iterative loops can also be used for other mechanical features, like wall thickness optimization, stress concentration on blends, cooling passages density and position, and many more.

4. CAD Data Exchange for manufacturing and inspection

Based on the problems typical for a CAD data exchange, a successful process map needs to be introduced to achieve the right level of trust for data management. All findings, reflections, and requirements are based on experience gained with global cooperation between the author and GE manufacturing sub-contractors during the overall Ph.D. study period.

4.1. Requirement for Neutral Format CAD data exchange

Requirements for neutral format data should be preserved for all definitions used directly in production. External software should be able to import and filter all data without errors.

A typical list of requirements:

- The solid(s) used to define the part
- All Manufacturing and Inspection Datums and Datum Coordinate Systems
- All datum target points and lines
- Product Manufacturing Information Data
- All pre-determined inspection points
- All supplemental geometry which is required to define a direction of measurement in Feature Control Frames (GD&T)
- All objects should be named appropriately (points, curves, surfaces)
- All final product's faces should be visible

Feature names in a specific CAD system can be recognizable only inside the original environment. There is a need to differentiate whether the specific object is named internally in a CAD system as a feature, object itself, or both. (example: point name – Fig.4.1). Feature name will not be exported to any neutral format file, and translation will cover only the object name. It can be confusing to a CAD engineer, but at the same time, it can be easily prevented by automated translation tools.

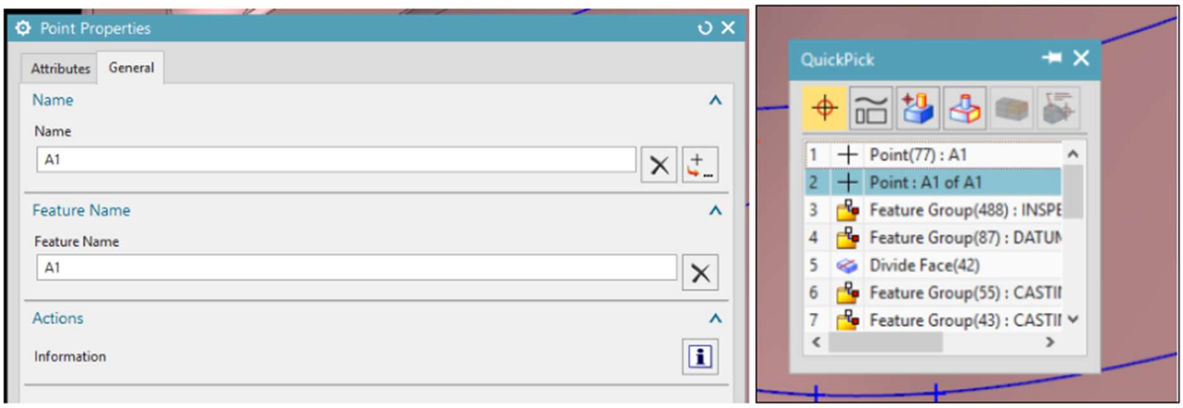


Fig.4.1. Point name and feature name comparison: The feature name is internal, the name is internal and external, and can be exported to a neutral format file.

The data should be checked before the official share with external collaborators. The most common errors which may occur during the translations are (Fig.4.2):

- Missing faces or bodies
- Missing assembly structure
- Missing points and curves needed for the part definition
- Extra faces, solid bodies, points, and curves coming from the model's construction, intentionally hidden in the original CAD file
- Wrong identification of the part file name (no or incorrect: description, revision et cetera)
- No inspection objects/features
- No objects identification

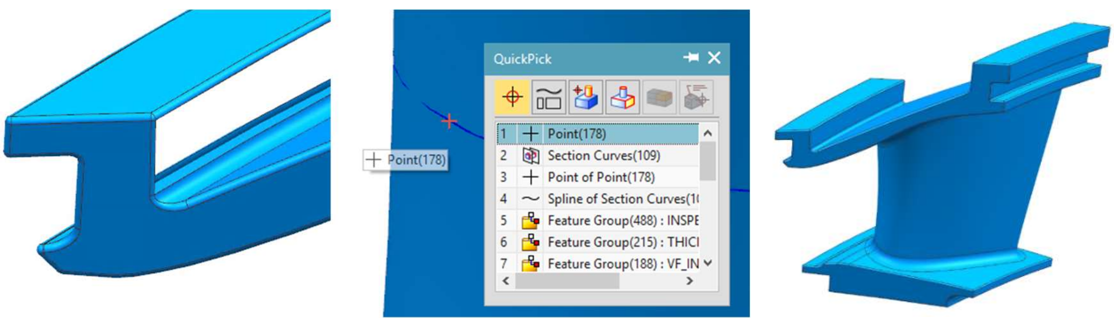


Fig.4.2. Examples of a missing feature name, face, 3D scan/CMM data.

4.2. Automation

Big CAD environments have dedicated and widely available open libraries to automate engineering work by simple macros and customized programs[14, 32, 40]. A model file should contain a separate reference set, a standard layer's group, a dedicated view – many solutions are available in case of the CAD type used. These may serve as a means to write company-specific quality checks and translators efficiently. A novel algorithm to automate the overall process has been proposed by the author. (Fig.4.3). A specialty toolkit verifies the consumption of PMI data and point-to-surface matching. If a quality test is passed, all "labels" and feature names could be converted. This verified data can be easily exported into STEP or IGES and shared with collaborators as a next step. Of course, the more "traditional" output can be automatically created (PDF, PNG) to maintain temporary or permanent compatibility with older techniques or people's habits.

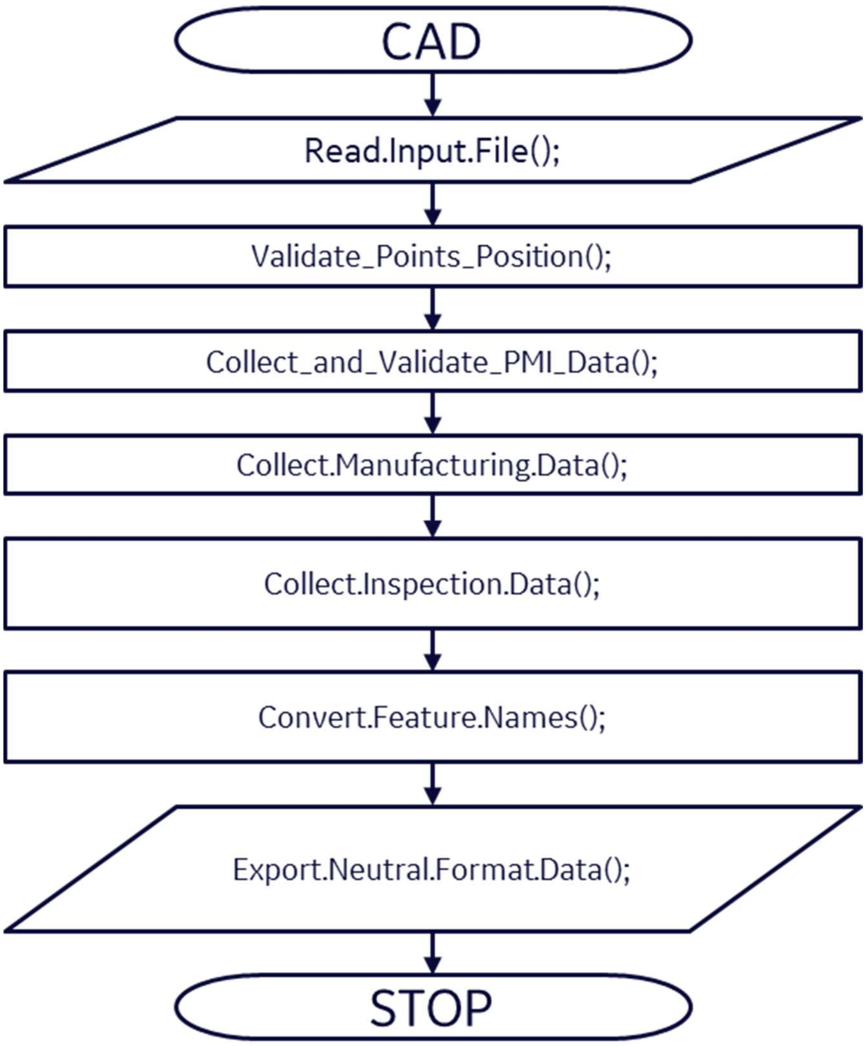


Fig.4.3. CAD data translation automation process.

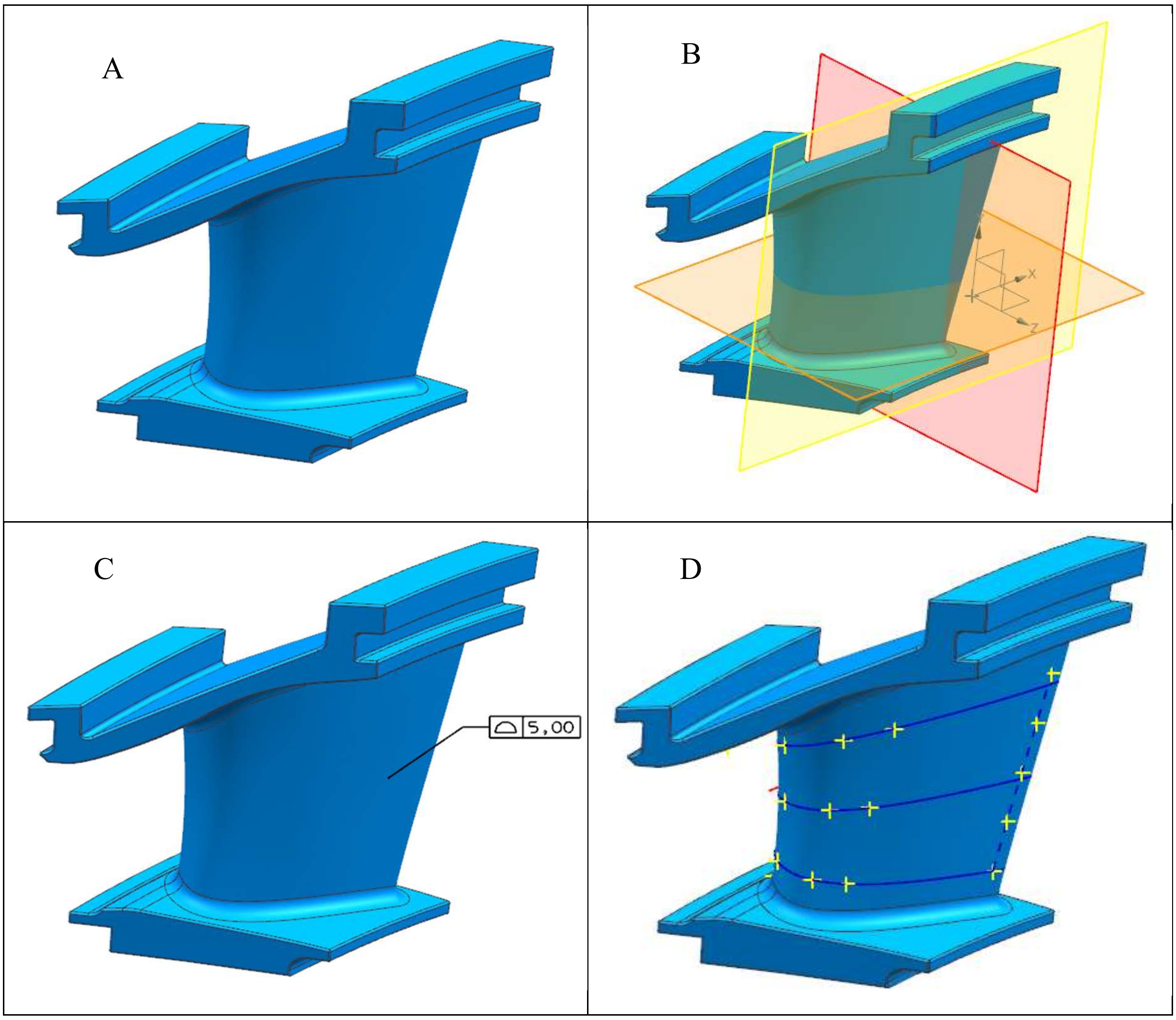


Fig.4.4. Four levels of MBE definition a) Solid geometry b) Datum System c) PMI definition d) Inspection data

There are four “levels” of definition that can be highlighted (Fig.4.4):

A) Solid - which is defining the overall nominal geometry

B) Datum Systems - to define the part position and manufacturing sequence

C) Product Manufacturing Information – plus/minus and geometrical tolerances (GD&T)

D) Inspection Data – a qualified manufacturing process does not need to inspect 100% geometry, so additional data is required for an inspection plan.

All of those are a key to a fully organized and demanded modern definition.

4.3. Results

The overall quality of translation based on a B-Spline/B-Surface tolerance is a critical factor, but stimulatingly also easy to be unnoticed. Even a significant deviation is hard to detect without specialistic and automatic macros or tools, as the real issues may not be visible to a human eye.

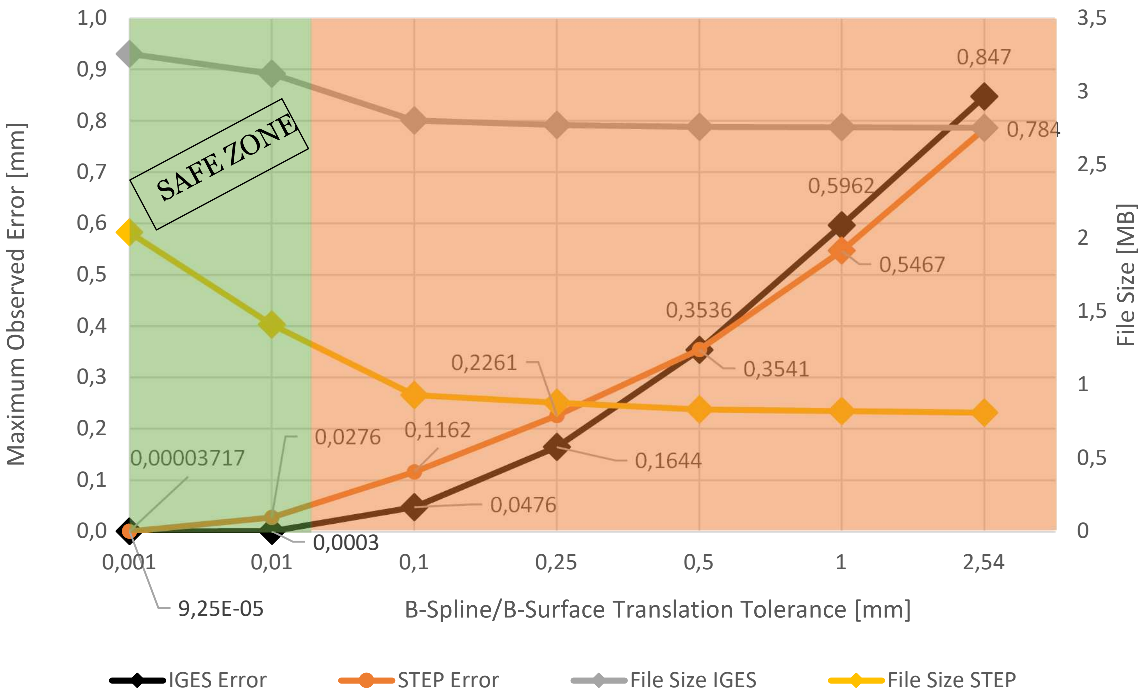
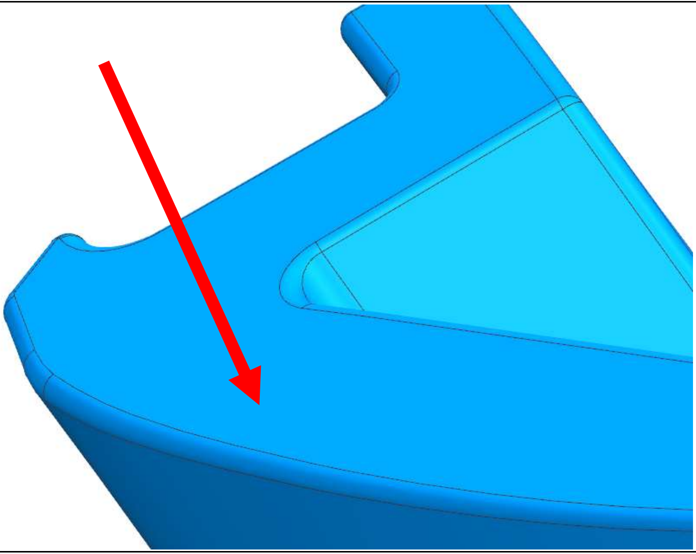
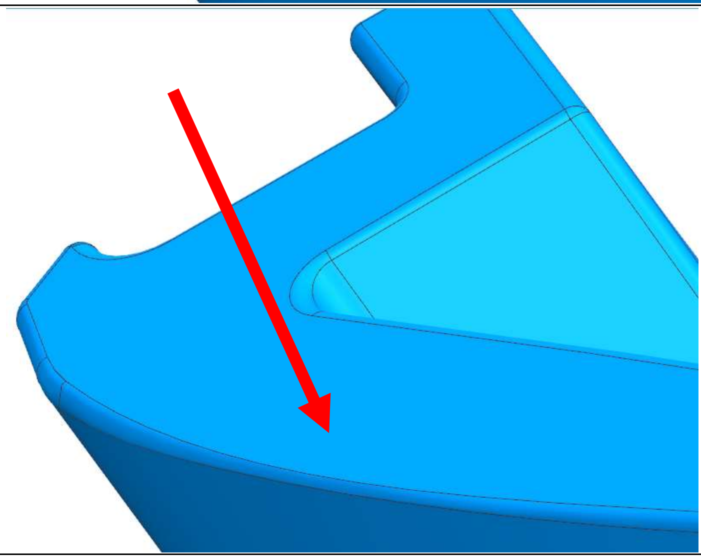
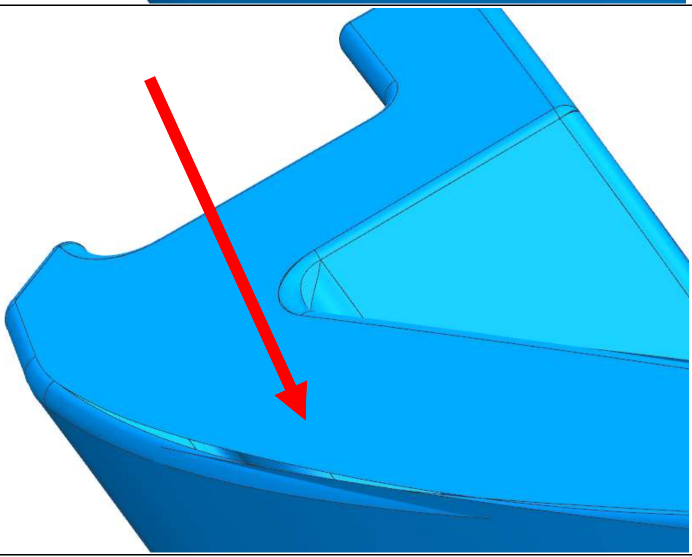


Fig.4.5. An average surface error vs. the original shape with a comparison of tolerance and file size.

Fig.4.5 shows an average surface error vs. the original shape with a comparison of tolerance and file size for a turbine guide vane model used by the author in this work. It is noticeable that the actual deviation is much smaller than the value set during translation from the original model. Both STEP and IGES translation seems to be on a similar level of quality/trust. However, the STEP shape error exceeds tolerance for 0.1mm translation (with a maximum error of 0.1162mm – a standalone deviation). IGES file size is very similar for all tolerances, while STEP conversion size growth is exponential. More extensive issues examples from the chart in Fig.4.5 are presented in Table 4.1. A straight borderline for safe translation cannot be defined worldwide but must be considered for a model size and complexity. The translation error can be severe for manufacturing if the value consumes main final part tolerances, or even worse, when if it exceeds any of these.

Table 4.1. B-Spline/B-Surface issues based on translation tolerance for STEP format.

B-Spline/B-Surface Tolerance	Result
0.001	
1.0000	
2.5400	

Commercial file format translators are commonly equipped with automatic checking tools, and those reports may be instrumental for quality checks. The quality of the direct neutral format translations for CAD definition should be prioritized and cannot be treated like a “save as” option by any CAD user. Awareness of the quality phenomena should be emphasized in business applications and academic lectures.

4.4. Discussion

The future of manufacturing lies in adherence to proper data quality management. We have already reached the point where some parts are impossible to manufacture using traditional methods and intended only for 3D printing. CAD Model is the only trustworthy source for complete specification, analysis, manufacture, use, and repair lifecycles. Neutral data seems to be the only rational solution used to manipulate within systems and software, and every modern company should introduce solutions for proper and automated data translation.

Changing an overall perception of a digital definition is strictly recommended, not copying any techniques of previous predigital (paper) practices. All data other tools and software can read may bypass “human interpretation”, so we would no longer need any tables, point labels, and similar features shortly. All those simplifications can decrease a lot of prototyping time, eliminate errors and save money in the end. The last step in the model-based enterprise ideology will be at our fingertips.

5. Inspection Enhancements

5.1. CMM Inspection – Simplification Process

5.1.1. New Methodology Enhancements

As the author proved [39], most academic research focuses on a path simplification process as a standalone process. The key to adding a novelty in this area is to merge path simplification with part mechanical objectives and focus on critical features. There are many other inspections needed to pass after part manufacture. The stabilized casting process does not need to control every single surface. We must check the material structure and stability by NDT methods. That is a place to control by CMM only the significant profiles of the airfoil surface.

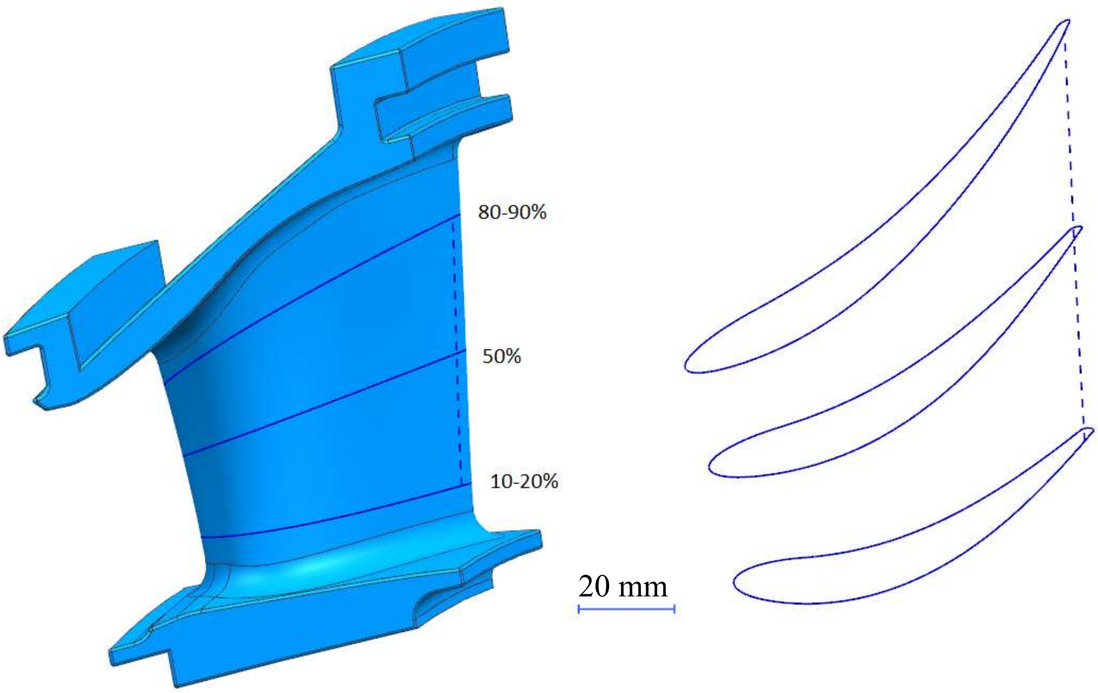


Fig.5.1. Turbine guide vane CAD Model with original CAD sections used for airfoil extraction with additional trend line. [39]

5.1.1.2. CAD defined sections

As presented in Fig.5.1, that set is the primary source for the CMM path probing for the overall airfoil shape in a horizontal plane. The overall number of such sections could vary depending on the part height. Typically, a set of 3-5 sections should be enough for inspection. The positions may vary and shall be moved outside the platform blends to eliminate the risk of fluctuations. In our case, such sections will be established on 15%, 50%, and 85% of the overall height.

Sections shall help meet GD&T requirements (Fig.5.2), which means we have a zone around the main profile. That is the acceptance zone where all measured points from CMM inspection shall be located. This spline can be simplified by knot removal methods to decrease measuring points and define improved CMM paths.

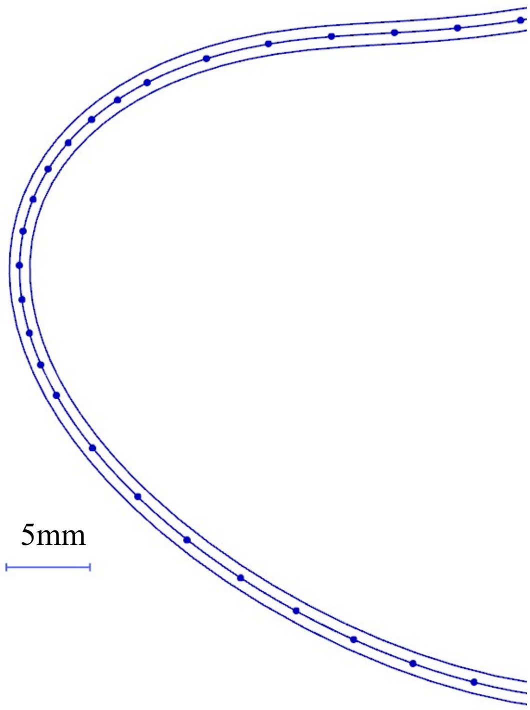


Fig.5.2. Airfoil 2D section with visualization of GD&T tolerance zone[39]

5.1.1.3. Trend line

A trend line is defined on a thin trailing edge surface (Fig.5.1) to control airfoil curvature in a vertical direction. The significant meaning of such a line is to check the overall airfoil shape curvature on the thinnest areas prone to deformation (Fig.5.3). The nominal position may vary. It is proposed to establish it at least 10mm from the theoretical end of a part. That could compensate for any possible shape distortions and still provide good feedback about these critical area conditions. Additionally, such kind of line can be moved on the throat area section for a later manufacturing process – for example, to check coating thickness in that place.

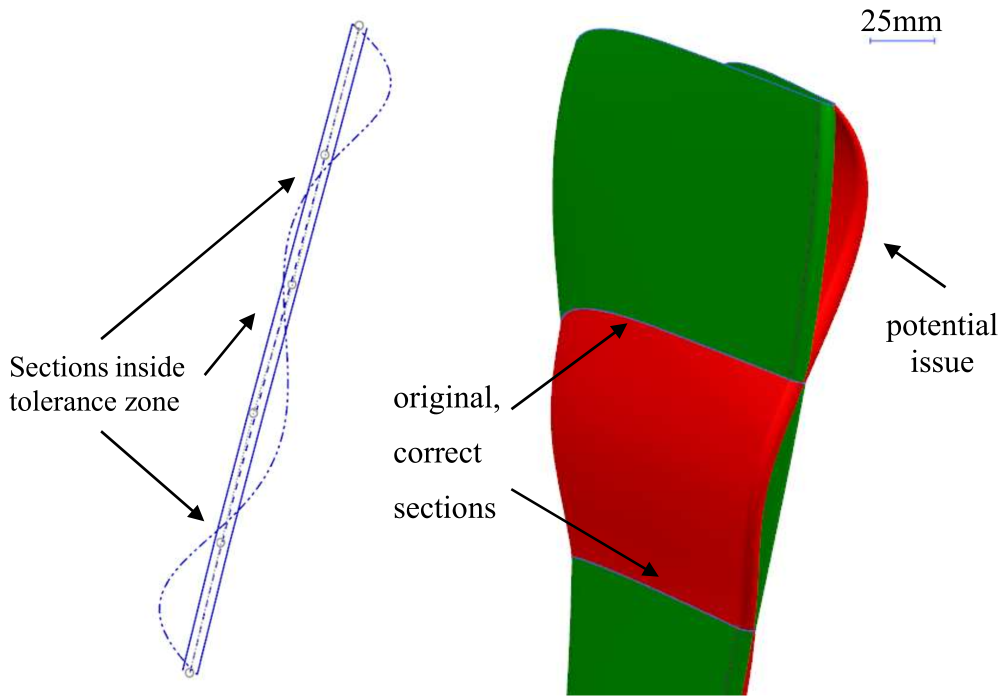


Fig.5.3. An exaggerated example of a potential miss during the inspection process. 2D sections measured separately can be within tolerance, while the overall airfoil shape may be bent/curved[39].

5.1.2. CMM path points removal

Similar to a CAD style, the CMM measurement path can be displayed as B-Spline with its knots. The initial sample spline used in the research was a collection of 104 Bezier curves and 104 knots (Fig.5.4). The other authors' extensive research [9, 21, 24, 48, 60, 61, 69, 82] shows that such collection will not be needed to perform an efficient measurement study. The already known knot removal process [9, 21, 24, 69] has been performed in this work. That allows identifying a satisfactory compromise between the count of points needed for inspection and the overall time for the entire process.

The first simplification process was to define a theoretical number of points sufficient for inspection, based on the shape distortion for the CAD spline. A scenario of how the shape behaves from 10 up to 1000 points (knots) has been performed. The study (Table 5.1 and Fig.5.5) shows that after reaching 25 points, there is no significant impact on the shape error. That means 25 knots may be used as a source of CMM inspection points coordinates. The standard engineering rule 1:10 states that if a method error is more petite than 10% of the tolerance, it can be used in practice. For the 1mm tolerance zone, this simplified spline is justified to use. The smoothness of a part spline will be maintained.

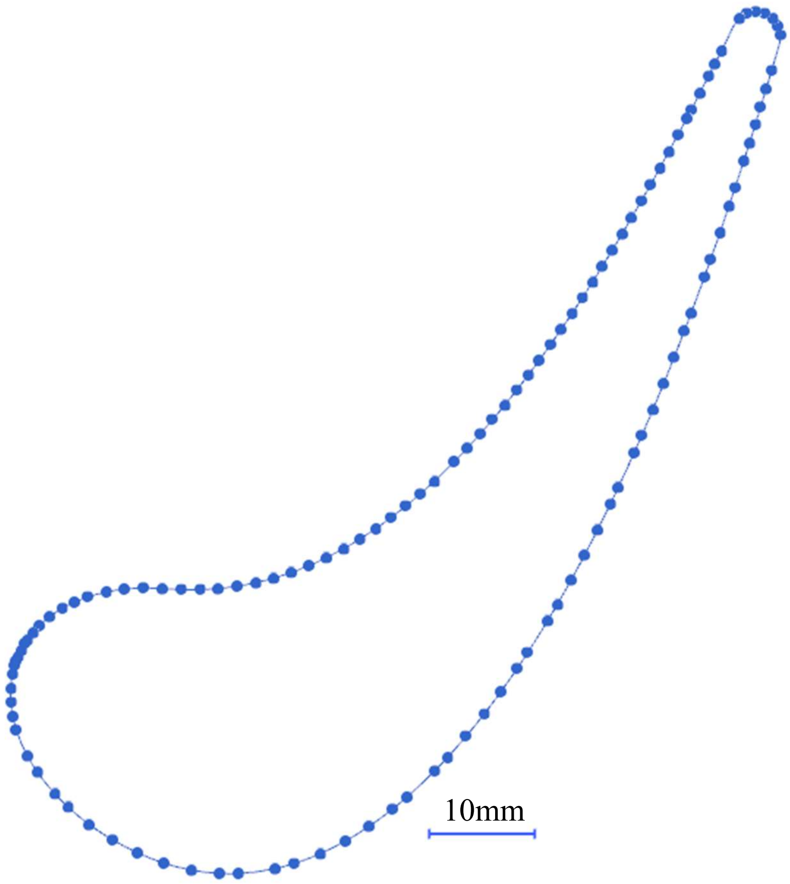


Fig.5.4. Initial control section as a collection of 104 Bezier curves[39]

Table 5.1. Distance error with relation to the knots used for simplified spline reconstruction. [39]

Number of points	Maximum Distance Error [mm]	Average Distance Error[mm]	Standard Deviation [mm]
1000	0.020	0.001	0.000
500	0.029	0.002	0.000
250	0.041	0.003	0.001
125	0.057	0.005	0.002
75	0.074	0.006	0.004
50	0.077	0.005	0.006
25	**0.085**	**0.009**	**0.009**
15	0.233	0.055	0.045
10	1.288	0.354	0.404

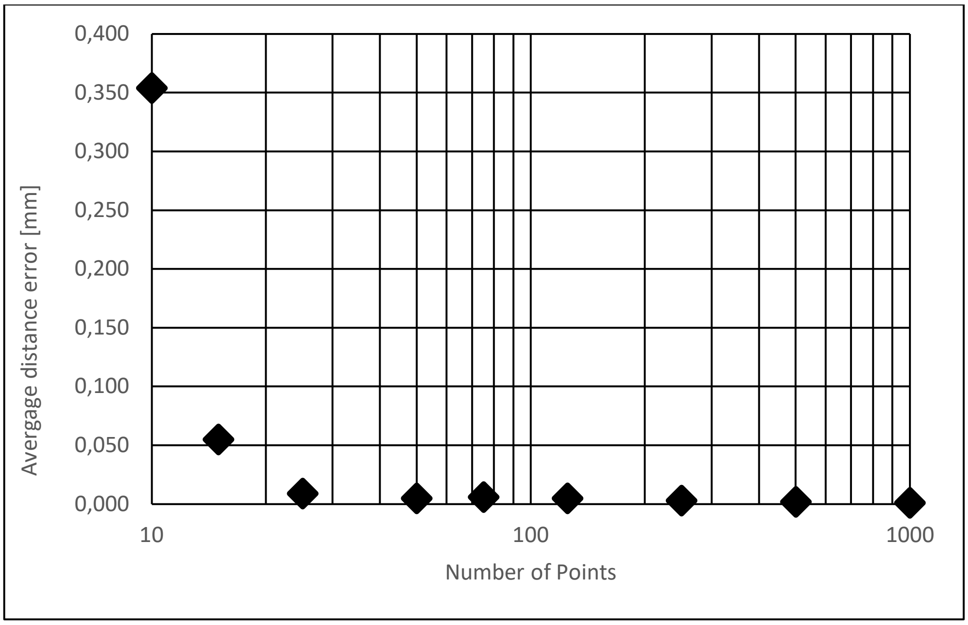


Fig.5.5. Distance error chart for the set of points in the range of 10-1000. [39]

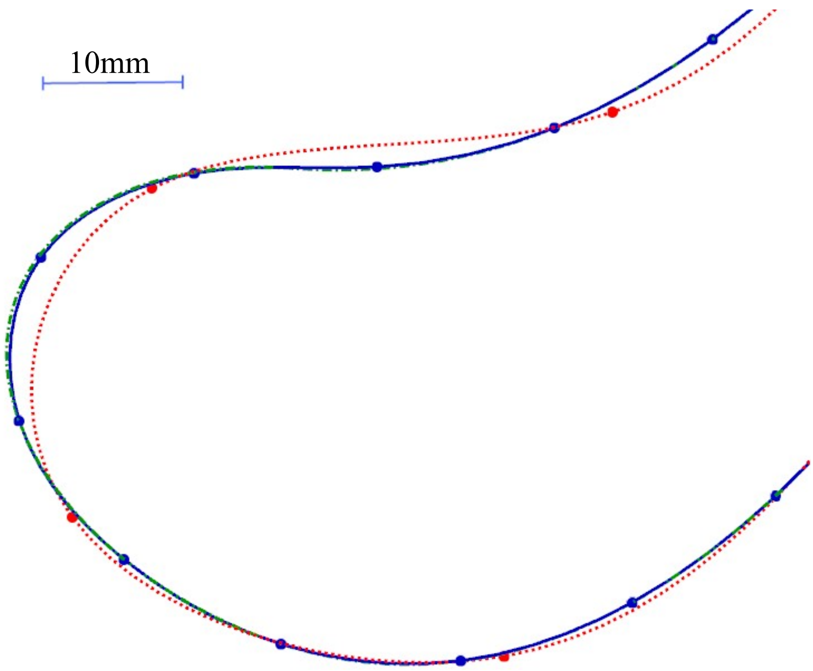


Fig.5.6. Overlay of three B-splines. 10 knots - red – dashed; 25 knots - blue – straight, 104 knots original - green dotted-dashed [39]

Visual interpretation of the study is presented in Fig.5.6. A too-small value for knots observed with 10-points translation can deform the shape too much, while 25 shall assure the same accuracy for the part inspection. The same observation can be re-versed to situations where 999 knots spline could report several dozens of points outside the same identified problem tolerance (Fig.5.7). That will not bring any benefit to the inspection process.

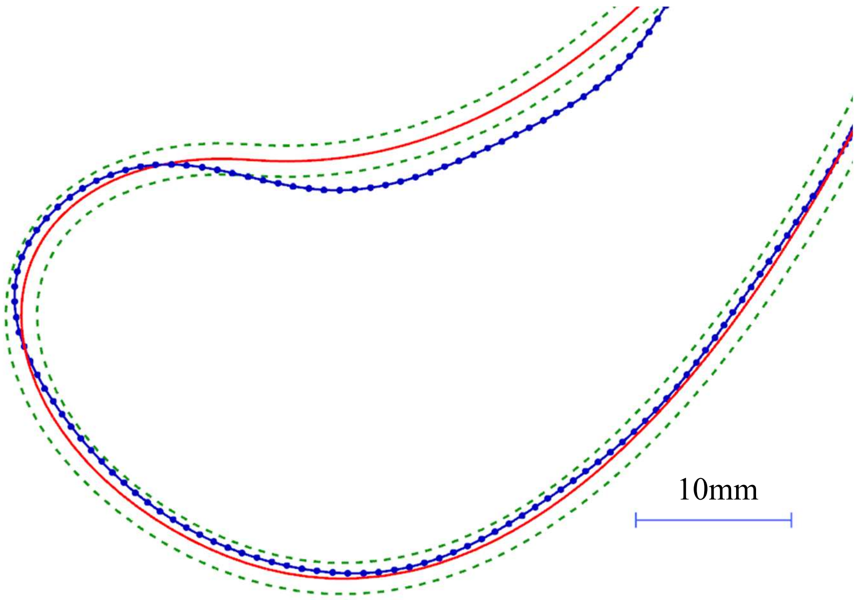


Fig.5.7. Nine hundred ninety-nine points on a B-Spline; blue dot line – deformed part shape exceeding the tolerance zone (green dashed line), red straight line – ideal shape [39].

5.1.3. Results

After promising results from theoretical divagations, genuine part has been measured on Zeiss Accura II, Calypso 2019 software with Curve and freeform module, Vast XT, and Vast XXT probe heads. The same situation was investigated to compare 5 to 1000 CMM points on two parts with surfaces issues (Fig.5.3) and without it (Table 5.2).

Cast surfaces have a higher tolerance range than precisely machined. That is why a tolerance range could be 1 to 2 mm and shall be inspected according to world standards (ASME [88]or ISO [90]). GD&T language has been developed as a universal language for every engineer and operator in the whole world.

Table 5.2. CMM inspection results for a turbine guide vane part without surface issues[39].

Part	Maximum Distance Error [mm]	Average Distance Error[mm]	Standard Deviation [mm]	Points outside the tolerance zone
1000	0.122	0.059	0.024	0
500	0.122	0.059	0.024	0
250	0.122	0.059	0.024	0
125	0.122	0.059	0.024	0
75	0.122	0.059	0.024	0
50	0.120	0.059	0.024	0
25	**0.103**	**0.060**	**0.024**	**0**
15	0.121	0.066	0.018	0
10	0.103	0.068	0.023	0

Table 5.3. CMM inspection results for a turbine guide vane part with surface issues [39].

Number of points	Maximum Distance Error [mm]	Average Distance Error[mm]	Standard Deviation [mm]	Points outside the tolerance zone
1000	0.787	0.322	0.215	256
500	0.787	0.322	0.215	119
250	0.786	0.322	0.215	59
125	0.785	0.321	0.216	30
75	0.786	0.322	0.213	18
50	0.786	0.324	0.214	11
25	**0.762**	**0.328**	**0.211**	**6**
15	0.695	0.328	0.221	5
10	0.695	0.352	0.180	2

Results from both tables prove that 25 CMM points provide reliable and representative measurements. There is no need to report the same surface issue more than once unless the discrepancy is long and critical to reject the part. Up from 125 points, a less precise scanning method has been performed to collect the data in a reasonable time frame. That is the reason why these groups have higher errors reported.

A comprehensive measurement for a turbine guide vane has been performed at the end to document and verify the full scope of the proposed method. It was divided into three profiles for airfoil shape and one trend crossing line for a curvature check. Results are presented in Table 5.4. The whole process took around 300s to complete with satisfactory records. All points lie within the desired tolerance, and the part could be accepted for the engine. An interesting observation for section 3 can be highlighted, as this area has more deviations but is still within the tolerance zone. A method has been proved and used to test the entire batch of production.

Table 5.4. Results from complete measurement session[39]

	Measured points	Maximum Distance Error[mm]	Average Distance Error[mm]	Standard Deviation [mm]	Time of overall inspection [s]
Section 1	25	0.127	0.047	0.032	<300
Section 2	25	0.102	0.055	0.025	
Section 3	25	0.635	0.265	0.155	
Trend line	16	0.645	0.303	0.229	

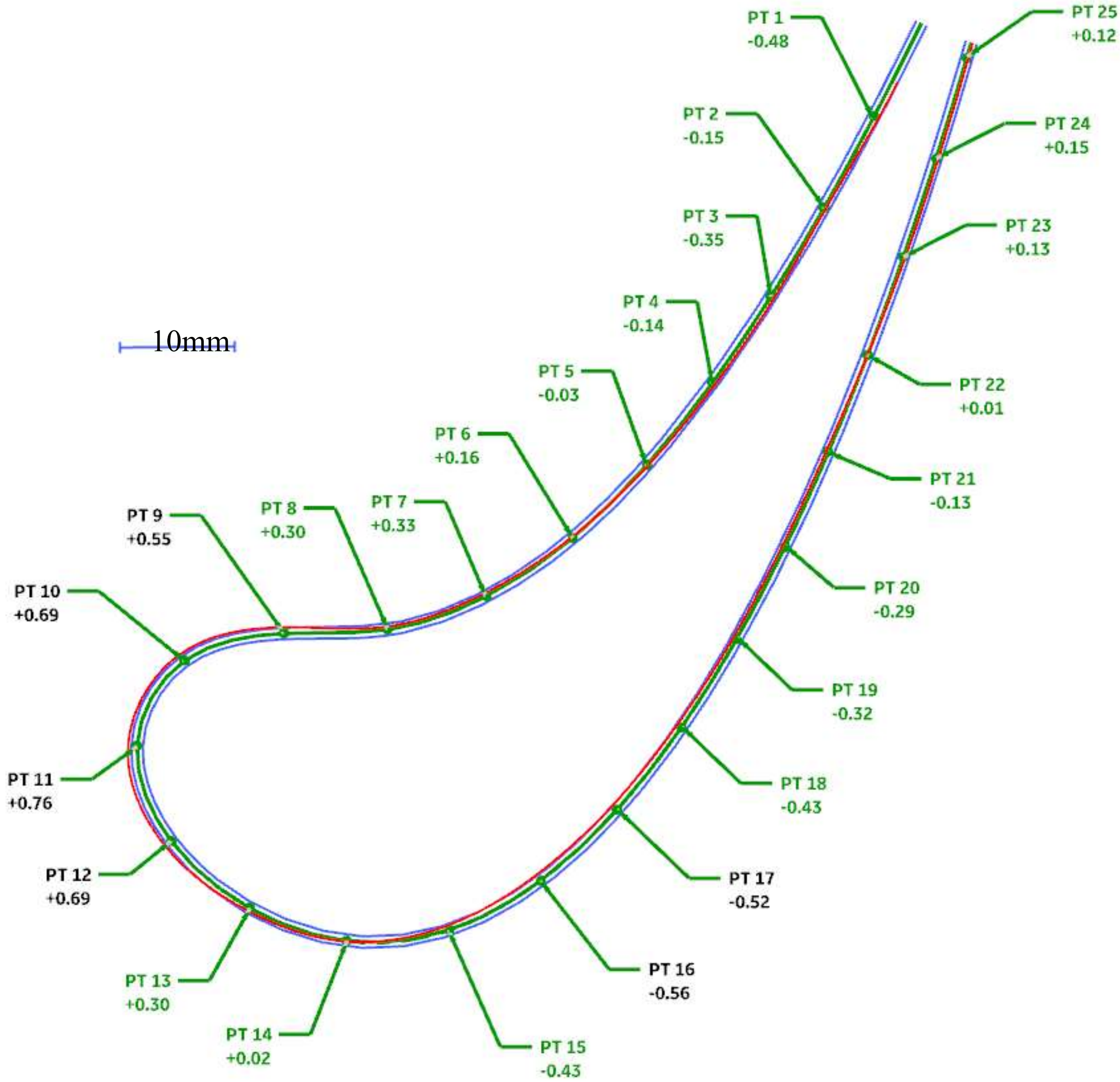


Fig.5.8. CMM inspection results for a turbine guide vane section with 25 significant points [mm][39].

5.1.4. Discussion

Each simplification for mass production is counted in real money. That is the universal law that has ruled the industry for decades. Even a slight adjustment can be significant for the company if it duplicates for every process instance. That is why such a field is rich with independent researches and willingly implemented in the industry. The other benefit is that the faster inspection of a one-part set is, the sooner another batch can be verified and transferred to the customer.

Even presenting results – as a graphic (Fig.5.8) - instead of the table could be considered as simplification. A potential error with the place of existence, marked on the spline, can be easily noticed and examined for its criticality and potential acceptance.

Atypical hybrid convention (vertical and horizontal crossing paths) could help maintain a correlation between independent sections and allow for decreased measurements.

Turbine guide vane has a complicated manufacturing process; that is why some enhancements can be used more often for the same part. Typically, there is from 3 up to 6 sub-processes like:

- Casting – production shape verification
- Machining – position and shape verification
- Coating – thickness check
- Heat treatment – deformation control
- Welding/brazing - overall shape and thermal distortions
- Assembling- engine check for equal flow distribution

Each of these processes has its inspection, where this kind of simplification can be implemented. Trend line position can be adjusted on the different steps to check different objectives.

A CMM path – B-Spline input should be translated in a neutral format to secure good inspection quality.

5.2. Optical Inspection – 3D scan risks and assessments

5.2.1. New Methodology Enhancements

The other research published by the author[38] proves that optical measurement could still provide uncertain results, which needs to be attentively verified and tuned to adapt the details from the manufacturing process.

Fig.5.9 shows an example of the first surface machined to define a datum for the following operations. Tight tolerance value has a significant meaning as a reference orientation for all other features. The surface is relatively small, as it is a rectangle with two dimensions of 5mm and 80mm. The measurement process should be precise and reliable, as possible deviation could negatively affect other features machined on a part. That is an easy task for CMM inspection, as this could be verified with the limited number of CMM points on the surface inside the smaller zone of safety.

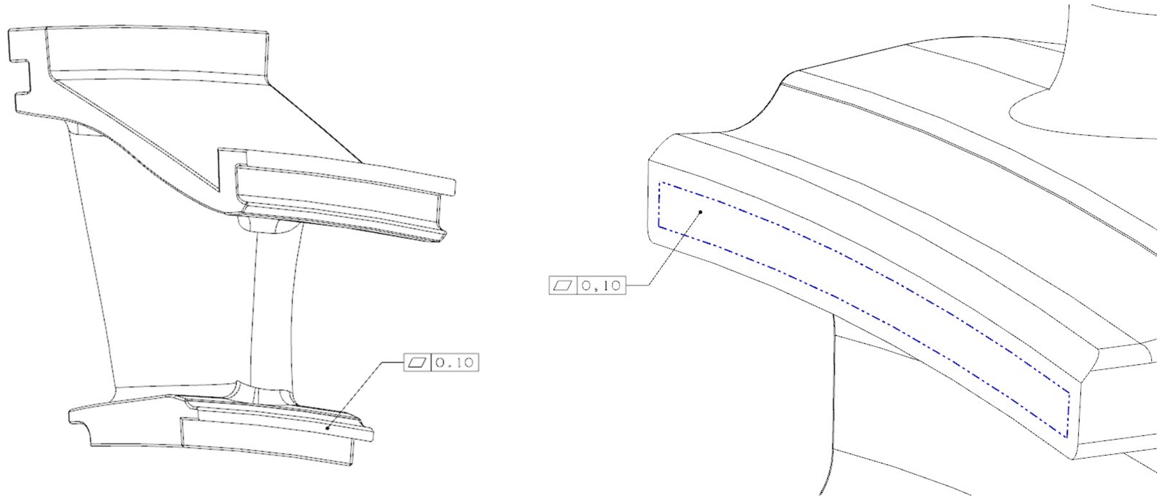


Fig.5.9. Flatness requirement for a datum placement (0,10 mm). Tight but critical tolerance example. CMM measurement zone on the right picture[38].

The situation may not be so evident for an optical method. An inspection for a set of 15 components was performed using GOM ATOS Core 3D Blue Light with accuracy 0.019mm and CMM machine from the previous chapter for reference.

The inspection (Table 5.5) shows values that were not consistent. While CMM presented parts primarily within the tolerance zone, optical inspection reported significant discrepancies. The reason for such inconsistency lies within the basics of optical technology. There are some casting blends on the genuine part, which were not introduced in a CAD file. Some of the points on a curved area were also used for a profile calculation(Fig.5.10). Geomagic Control X has no built-in filters to compensate for this phenomenon.

Table 5.5. Measurement results for the same surface, repeated for a turbine guide vane set[38].

Measured Vane	CMM Flatness	Flatness measured on raw 3D scan	The difference [3d scan vs. CMM]
1	0.070	0.077	9.09%
2	0.069	**0.149**	53.69%
3	0.066	**0.132**	50.00%
4	0.098	**0.132**	25.76%
5	**0.109**	**0.136**	19.85%
6	**0.103**	**0.145**	28.97%
7	0.079	0.084	5.95%
8	0.082	0.094	12.77%
9	**0.105**	**0.159**	33.96%
10	0.068	0.073	6.85%
11	0.070	0.078	10.26%
12	0.062	0.065	4.62%
13	0.051	**0.106**	51.89%
14	0.078	**0.153**	49.02%
15	0.079	**0.115**	31.30%

The author developed and tested an enhancement to achieve the same inspection accuracy for traditional and optical methods. The proposed method identifies and removes small contours from a 3D scan before inspection (Fig.5.11). There are some available studies made to achieve similar results like Di. Angelo[5, 6] to identify and insect blends and chamfers or Li[47], who improved the Harris algorithm, which is used in practice for such feature extraction. Contrasting the available tools and algorithms documented by these researchers, a simplified and easy to implement algorithm has been developed.

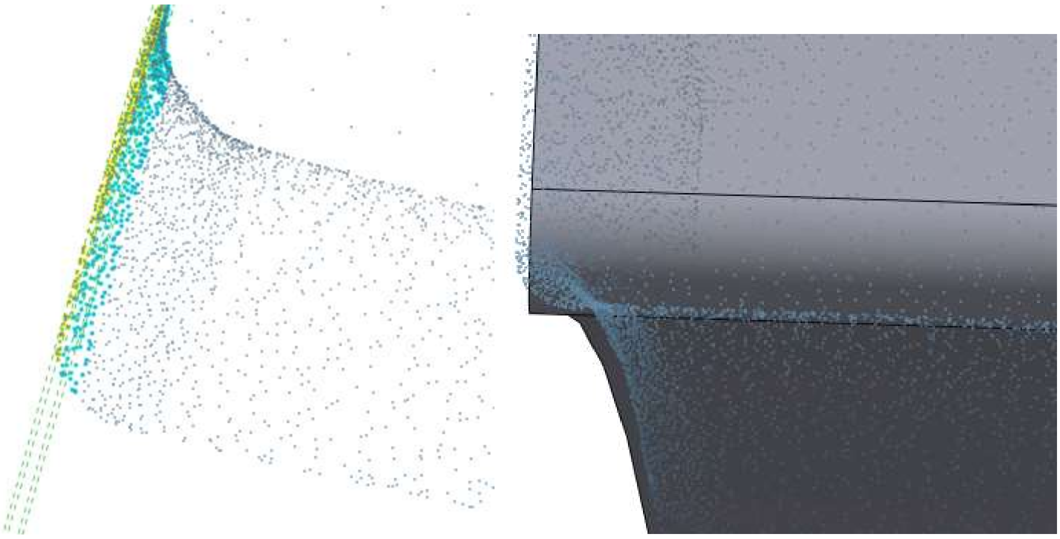


Fig.5.10. Geomagic Control X inspection. Some of the points used for a flatness inspection come from a "blend" area, not introduced on a CAD model[38].

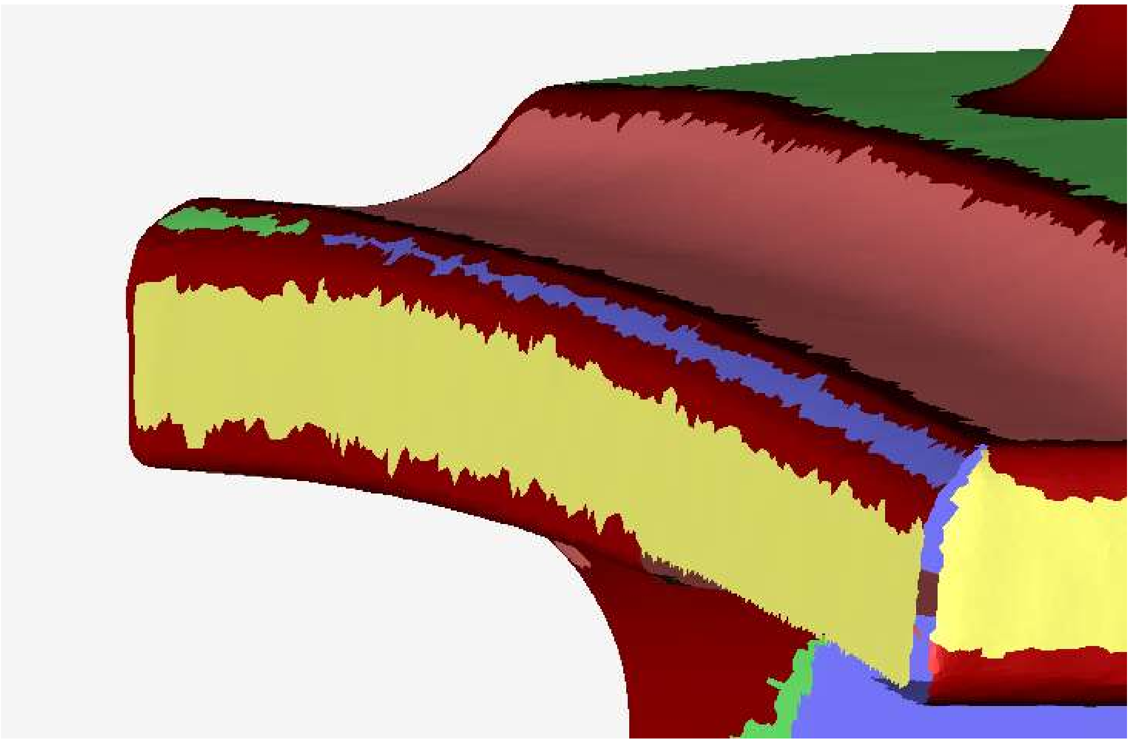


Fig.5.11. Surfaces identified on a 3D raw scan with small contours to be deleted from the file[38].

5.2.2. 3D Scan Contours defeaturing

The new idea of the contour defeaturing method is to divide all triangles into smaller groups with one common point (Fig.5.12) and then perform a local test for curvature (Fig.5.13). Of course, the triangles will be repeated in many groups, which increases accuracy on the "edges." According to one group, some triangles could lie on a "flat" area and a "curvature" area within another. That will define a safety margin similar to CMM methods if these triangles are removed too.

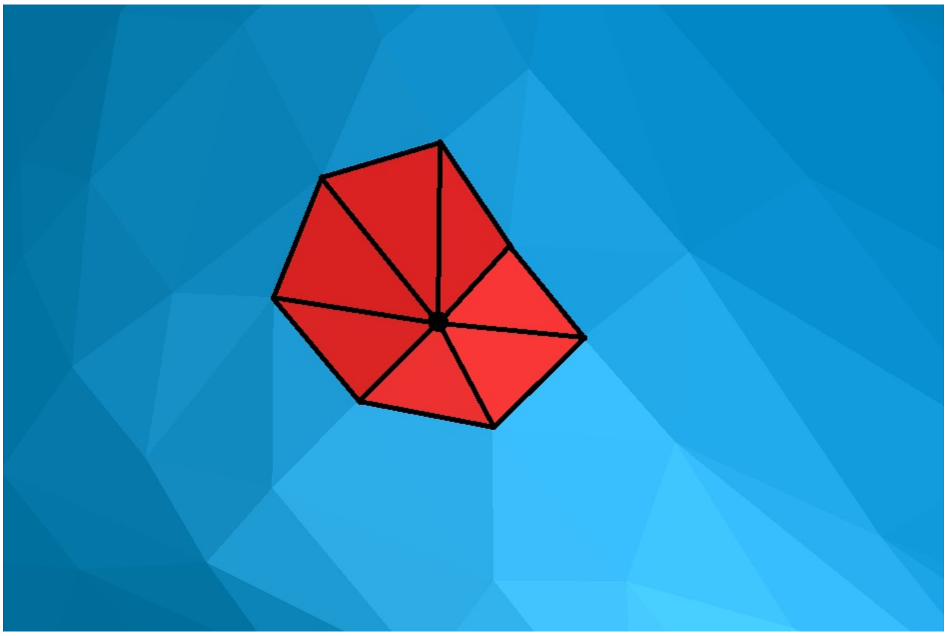


Fig.5.12. Example of a group of triangles sharing one common point[38].

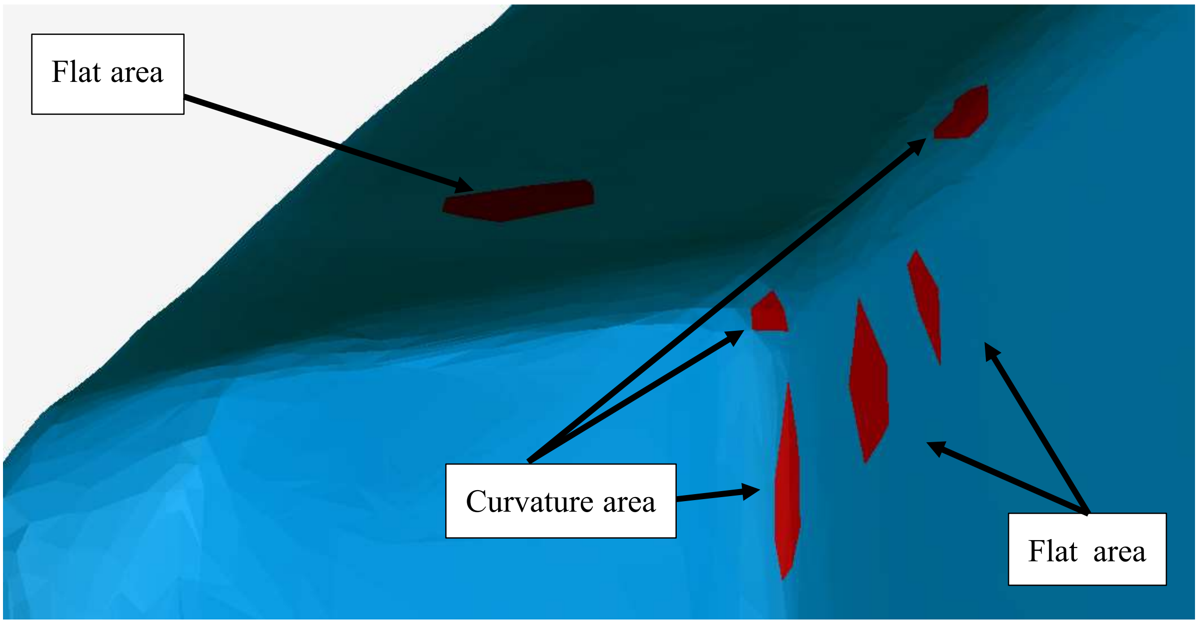


Fig.5.13. Different types of triangle groups (local flats and local curvatures)[38].

Local pairs can be compared within each selected triangle group to check if they lie approximately on the same plane (Fig.5.14).

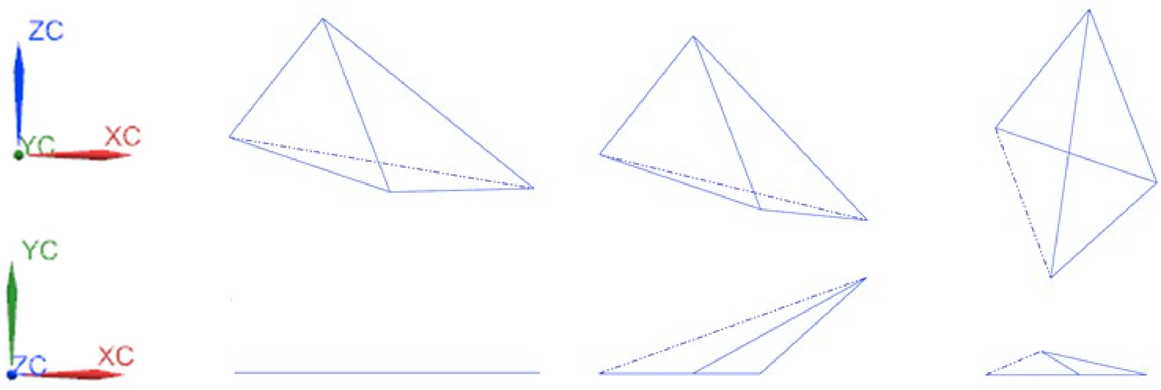


Fig.5.14. Two triangles would lie on a flat surface if the distance between two not shared points (dashed line) reached a local maximum. The smaller distance it has, the more curved surface they represent[38].

For that purpose, three terms need to be introduced (Fig.5.15):

- F – flatness indicator
- aL – actual length – the 3D distance between 2 not shared points from a triangle pair
- tL – theoretical length - the 2D distance between 2 not shared points from a triangle pair simulated to lie on the same plane

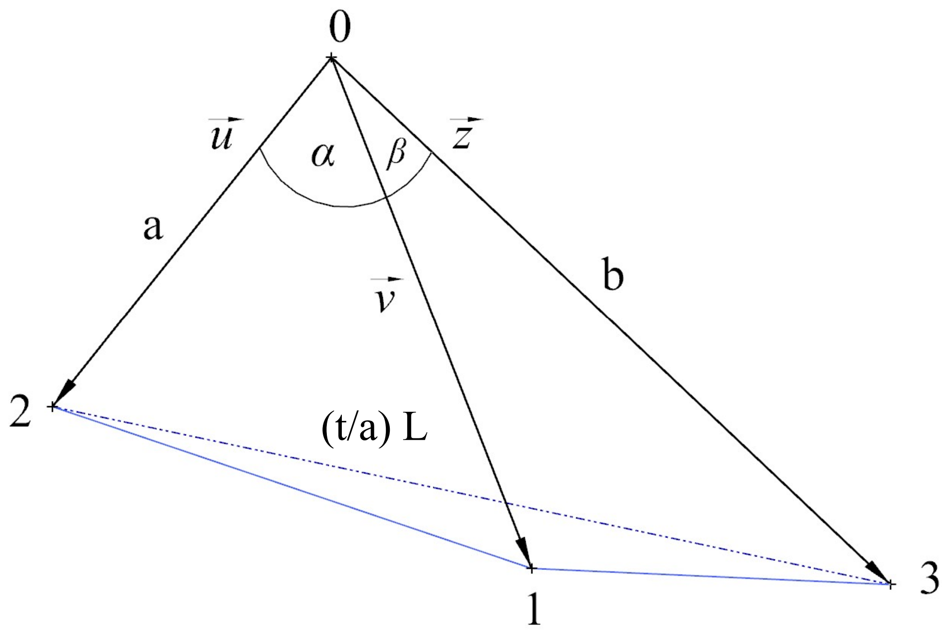


Fig.5.15. A pair of triangles. aL is the 3D distance, while tL is the theoretical value which can be calculated using trigonometrical equations[38].

We know all points coordinates from the STL file, so the vector formulas can easily calculate all the distances. That is also how we can measure the distance aL. For tL we need to calculate the theoretical value for θ angle, which is the sum of two other angles:

$$\theta = \alpha + \beta = \arccos\left(\frac{\vec{u} * \vec{v}}{\|\vec{u}\| \|\vec{v}\|}\right) + \arccos\left(\frac{\vec{v} * \vec{z}}{\|\vec{v}\| \|\vec{z}\|}\right) \tag{5.1}$$

$$tL = \sqrt{a^2 + b^2 - 2ab * \cos\theta} \tag{5.2}$$

If aL is equal to tL, then we could assume perfect local flatness. In a real scenario, this ratio will vary from 0 to 1:

$$F = aL/tL \tag{5.3}$$

$$F \in <0;1> \Leftrightarrow 0 \leq F \leq 1 \tag{5.4}$$

Based on the test performed by the author, an F with a value higher than 0.998 was set as the criterium for a local flat. Smaller values are identified as a local curvature. Because some curvatures are intentional, there was a need to identify small contours to delete from a file and keep the rest. We need to follow a similar approach proposed by Tao[76], Palma[59], or Jagannathan[37], but more straightforwardly. To calculate a radius (Fig.5.16), the universal formula for a circle circumscribed about a triangle can be used with the combination of Heron's formula:

$$R = \frac{l_1 * l_2 * aL}{4P} \tag{5.5}$$

$$P = \sqrt{\frac{(l_1 + l_2 + aL) * (l_1 + l_2 - aL) * (l_1 - l_2 + aL) * (-l_1 + l_2 + aL)}{16}} \tag{5.6}$$

$$l_1 = \frac{a * \sin\delta}{\sin\alpha} \tag{5.7}$$

$$l_2 = tL - l_1 \tag{5.8}$$

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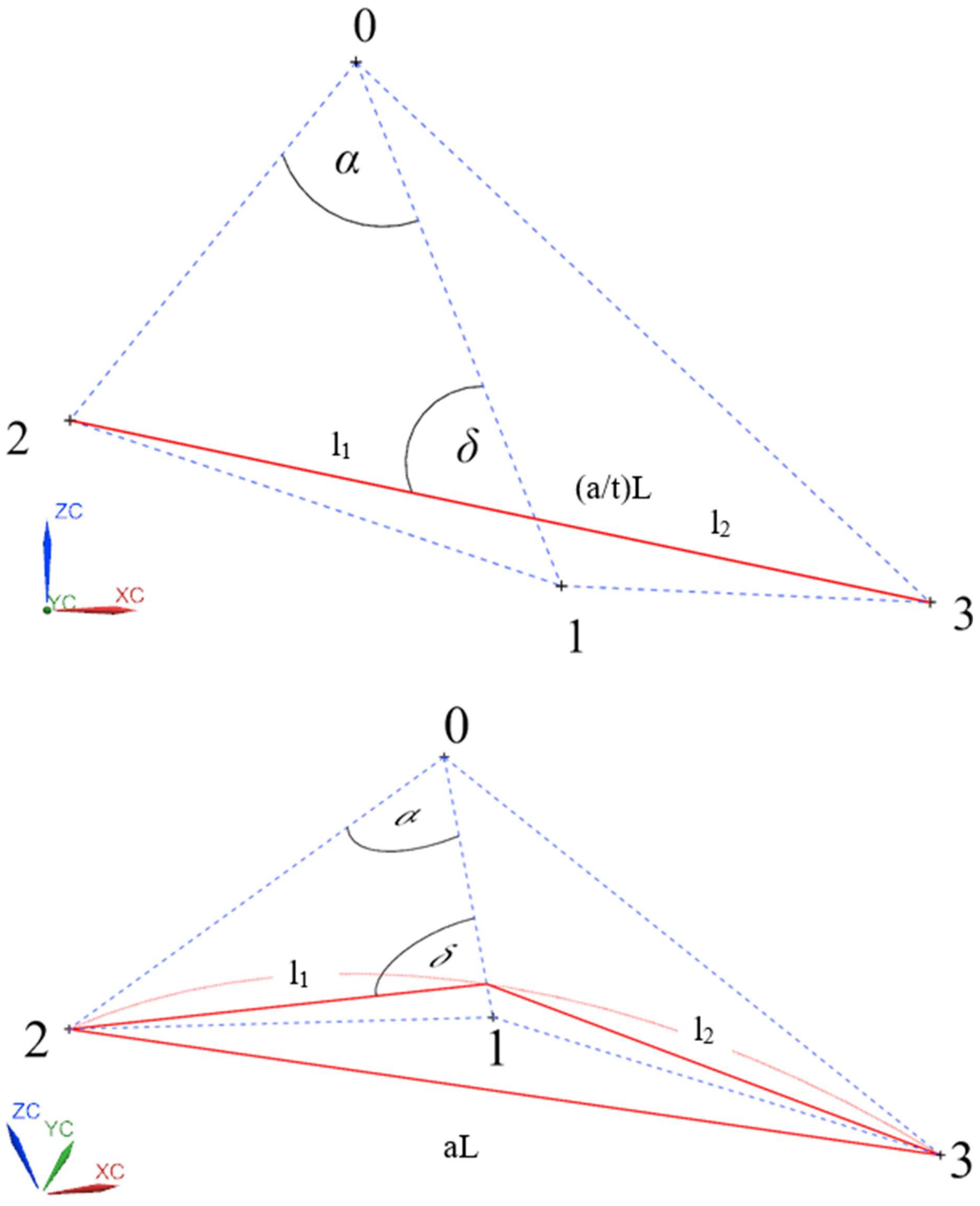


Fig.5.16. The higher picture describes formulas designations. The lower picture shows an isometric view with a partial circle on it. $tL = l_1 + l_2$[38].

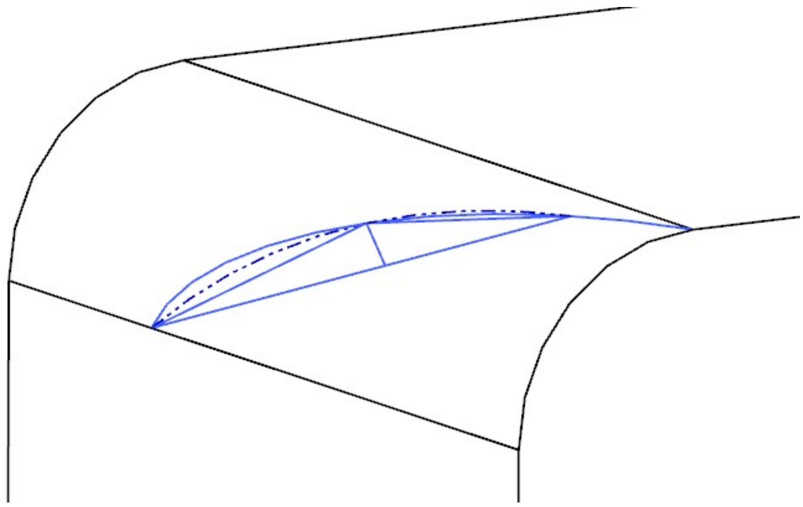


Fig.5.17. Chaotically spread triangles shall be treated as a part of an ellipse[38].

The local radius for a pair of triangles is only the estimation of the bigger surface. In the 3D, scan triangles are spread chaotically, so they can only be calculated for the estimated radius using the significant data set. Commercial software is written in the same way to calculate values only from a more extensive set of data. For a local purpose, this value can be distorted too much. These phenomena can be visualized as an ellipse deformation (Fig.5.17). To compensate for this scenario, an ellipse enlargement (EE) factor has been introduced. A study performed on a 1mm blend surface shows a variation between 0.4-1.6mm (Table 5.6). Based on this, EE was set as 1.6. In other words, measured values that need to be deleted can vary in the range of 0.4 to 1.6 of the nominal value. If the minimum intended curvature starts from 5mm, there is still a good margin for data filtering.

Table 5.6. Average radius calculated from an extensive set of data[38].

R (theoretical exact) [mm]	R (average for all pairs)	Median	Sample Standard Deviation	Number of triangle pairs
1.0	0.971836	0.822039	0.607124	4771

With all the boundary conditions collected, the author has encoded a final script (Fig.5.18). The tool goes through all triangles to group them into arrays according to the criteria of one common point. A simple method C#: list.Sort() is used there, but more advanced methods can also be found in literature, e.g., k-nearest neighbor or homogenous neighbor [47].

Each group is calculated separately, one by one, checking the flatness indicator ratio (F). The radius value is calculated using the EE (ellipse enlargement) factor if the local curvature is found. All groups marked with small curvature contours are deleted, and the final STL is re-written with the remaining triangles. Features recognized to delete from a file are presented in Table 5.7.

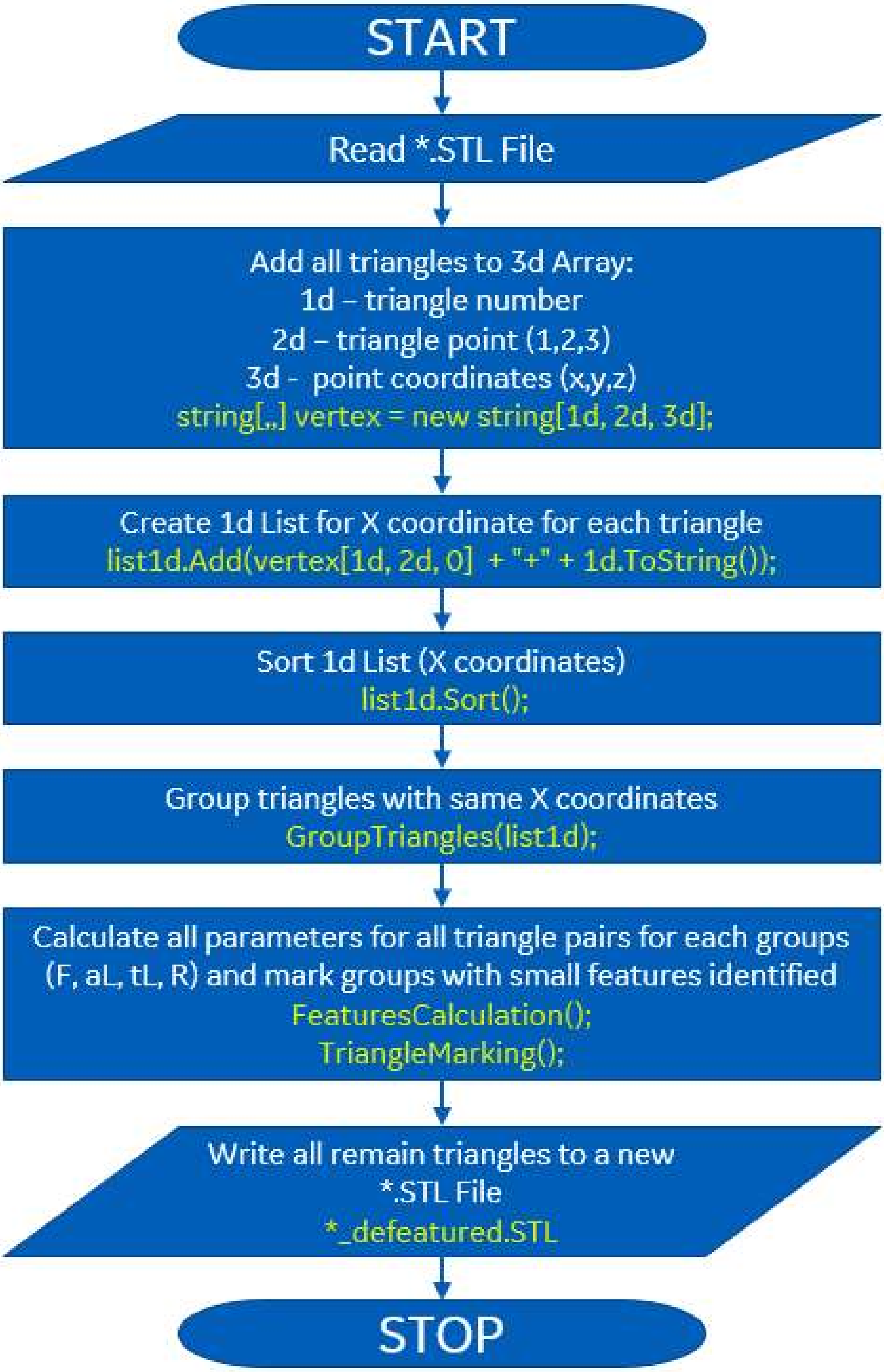
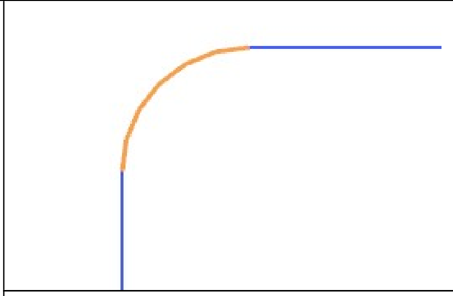
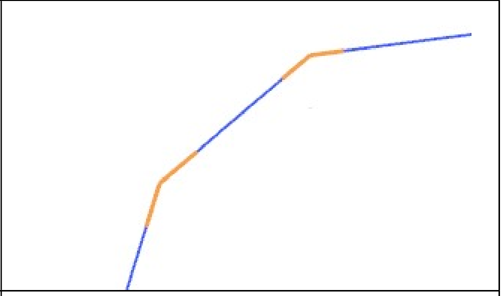
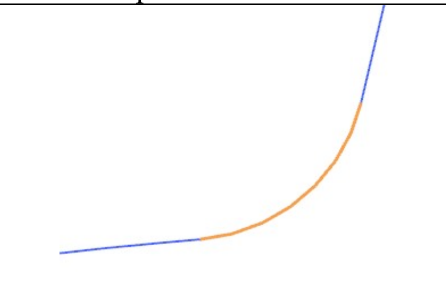
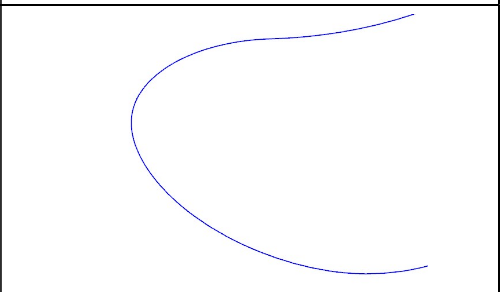


Fig.5.18. Final algorithm coded in C# environment[38].

Table 5.7. Features intended to remove during the de-featuring process[38].

Type of features	blend	chamfer
To be deleted		
	R = 1mm	1 x 1 mm
Type of features	Specification blend	Airfoil curvature
To maintain		
	R > 15mm	R > 100 mm

5.2.3. Results

When the enhancement has been developed, a comparison with the CMM method is truly justified. The same set of vanes 3D scans has been re-used for re-calculation (Table 5.8). The CMM method accuracy: 0.0012mm, while 3D Scan accuracy: 0.019mm. A defeatured example is presented in Fig.5.19.

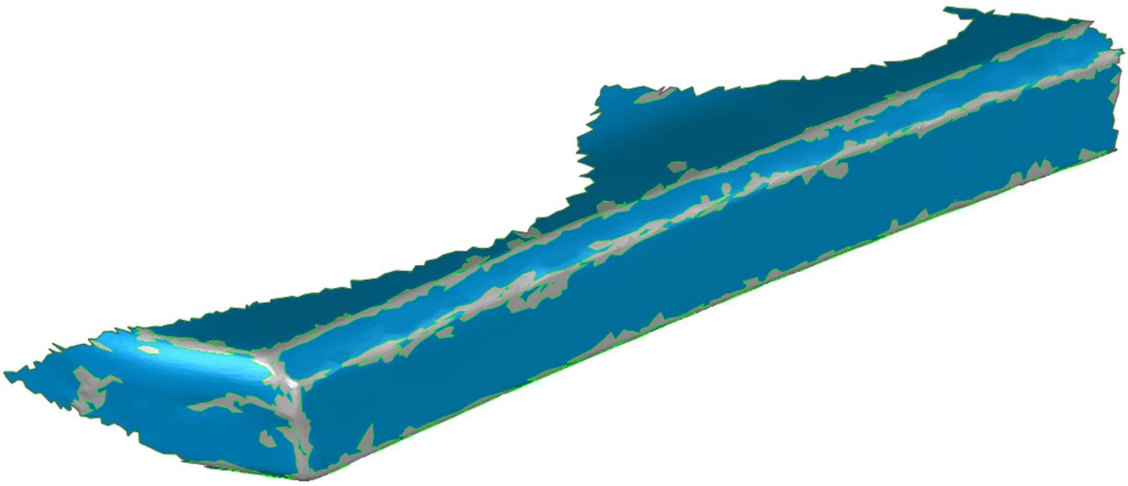


Fig.5.19. De-featured example for a surface flatness inspection[38].

Table 5.8. Additional defeaturing on the same set of scans with a comparison with the CMM method[38].

Measured Vane	CMM Flatness	Flatness measured on raw 3D scan	The difference [3d scan vs. CMM]	Flatness measured on a scan with removed contours	The difference [3d scan vs. CMM]
1	0.070	0.077	9.09%	0.076	7.89%
2	0.069	**0.149**	53.69%	0.074	6.76%
3	0.066	**0.132**	50.00%	0.069	4.35%
4	0.098	**0.132**	25.76%	**0.108**	9.26%
5	**0.109**	**0.136**	19.85%	**0.132**	17.42%
6	**0.103**	**0.145**	28.97%	**0.111**	7.21%
7	0.079	0.084	5.95%	0.082	3.66%
8	0.082	0.094	12.77%	0.083	1.20%
9	**0.105**	**0.159**	33.96%	**0.113**	7.08%
10	0.068	0.073	6.85%	0.069	1.45%
11	0.070	0.078	10.26%	0.071	1.41%
12	0.062	0.065	4.62%	0.065	4.62%
13	0.051	**0.106**	51.89%	0.055	7.27%
14	0.078	**0.153**	49.02%	0.079	1.27%
15	0.079	**0.115**	31.30%	0.083	4.82%

The results are very satisfying, as the measured set achieves a similar range to the CMM methodology. There is still one additional part that falls out but is still very close to the CMM data result. One part kept the higher value for a flatness. The reason for both is simple. While CMM inspection is based on around 200 points, the scan uses a much higher range for even 5000 points of such surface entirely. CMM also has a safety margin and verified a smaller portion of the surface.

Another fact is that not every scan is needed to perform such modification, but it is still genuinely justified to calculate the whole batch using an automatic tool. Time impact is not such significant, as the one scan needed less than 2 minutes to adapt.

5.2.4. Discussion

Even a well-performed 3D scan process could reveal some flaws and distortions. Scan optimization is not apparent and may deform the shape too much. Some deviations could be unnoticed, especially without a confirmation from a different inspection process.

Precision in measurement is the crucial aspect both for the final customer and for the manufacturer. All parties involved in the engineering industry share need to trust the approved processes. It is not unusual that the engineering desk can be in a different part of the globe than the manufacturing site. The destination client is also located in another place. The original engineer may see or may not ever see his component in reality.

The critical importance of the inspection method interchangeability lies strictly within the accuracy and repetitive results. CMM is still a method with a higher level of trust, but optical scanning can become equal shortly. That can happen nowadays when the operator's awareness of limitations and restrictions will be satisfied and secured. Commercial tools shall be upgraded for the broader application, and standards like ISO or ASME must be created similarly to the CMM world.

The proposed algorithm is simple (~1000 code lines) and fast (less than 2 minutes for a range of 1 million triangles). The complete set needed in the engine – around 50 parts would need less than 2 hours to complete[20]. That is a typical result like other commercial solutions. Proper data filtering could make 3D inspection interchangeable with a classic CMM inspection. The future lies there, as the optical method could visualize the entire part, inspect more points simultaneously, and provide more transparent reports. The presented method could be used for all parts, and the turbine guide vane is just an example.

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6. Summary and Conclusion

The thesis provides a technical guide through key findings observed during the turbine guide vane lifecycle. Main processes like part development, production, or inspection are the apparent steps with repetitive results. Smaller steps like data translation, optimization, simplification, or filtering plays still an important role in improving stability, accuracy, and schedule.

6.1. Research contributions

Thermal deformation is an unobvious aspect of the part development process. Current software and tools allow engineering a part in the natural working environment virtually. That means that a part working within a high-temperature condition has a different production shape, which must be thermally reverted for manufacturing purposes.

In this work, a mass collection of thermal deformation processes has been studied to define main and repetitive behaviors typical for a turbine guide vane components. A new algorithm has been proposed to introduce thermal scaling, which can be used for prototyping. The critical thing is that part development is a long-term process and needs many engineering adjustments to achieve a thoroughly reliable and competitive product. Thermal scaling needs to be introduced on every meaningful step to achieve accurate and reliable results for the analysis to confirm the right shape of a part.

Two iterative solvers (Powel and Conjugate gradient) have been studied and compared to automate and provide easy use of such conversion matrix algorithm. It has been proved that the fast Powell solver can be used for a big thermal loop. The proposed algorithm achieved ten times better accuracy than the rough scaling method for an initial shape without details (simplified solid shape vs. fully defined cooled final part).

When the part is successfully developed virtually, a proper shape translation for manufacturing purposes is a crucial aspect. As it is observed nowadays, the CAD model quickly became the primary source for production purposes. Drawing definition is now somewhat a relic of the past, with only a supportive function to maintain human interpretation. Complicated components cannot be fully defined on paper as mathematical equations are not intended for technical drawings.

In this work, the main trends of data sharing have been compared and verified for accuracy. It has been proved that data translation is not an obvious step, and the formal requirements should be set to secure an acceptable quality between different systems. Many formats are available, but their limitations should be considered, as some information could disappear during translation.

Another important aspect is that the CAD file is not only a product definition but this can and should be re-used for inspection. To secure a proper process, additional data needs to be translated. Typically a translation is intended to convert a solid body representation. STEP/IGES files with additional points and curves with proper names are the formats that shall satisfy all industrial collaborators. That is a bridge for achieving an MBE philosophy in practice. An automatic process to satisfy all requirements has been proposed. Such a method is not well standardized yet but is genuinely justified to implement it globally.

A manufactured part needs a stable and – what is most important - fast method to verify the specification intent. There have been many algorithms developed to simplify CMM inspection over the years. A new process has been established with the knowledge of the CAD data sweeping process, aero requirements, trailing edge bending tendency, and additional casting co-inspection. An additional novel enhancement for such a process has been proposed to connect the turbine guide vane's data translation and main mechanical features.

The critical aspect of a simplification process is to check the overall horizontal airfoil curvature with a cross trend line which can control vertical deviation. Such inspection is fast, reliable, and can control the essential aspect of the turbine guide vane: the throat shape variation. As the trend line position can vary, other initial development processes like casting can control overall airfoil curvature and trailing edge conditions.

A global trend to take advantage of 3D optical scanning inspection techniques can be observed. That is genuinely justified, as the overall scan shape can be easily overlayed into an original 3D solid to inspect all deviations. A simple comparison has been made to verify if the modern optical 3D scan method can be used equally to the most reliable CMM method. The small surface inspection has been performed on the same set of components to compare the results.

Initially, results were incompatible, as the difference observed reached even 300% of discrepancies. Optical scans use a point cloud for the entire surface with surrounding neighbors. CMM has limited space with a minor point collection secured from the part edges. As identified in this research, production blends or chamfers can perturb the results on small areas if they are not introduced in the original CAD model.

A new algorithm to remove such contours from a 3D scan file has been developed to eliminate such issues and allow a proper inspection. This automatic tool compares the triangles inside the file to check if they lie on a region of curvature or not. The provided filtering criterium removes all contour triangles from the file and allows a proper inspection. A filtered data has been compared with the CMM initial inspection, and the results are very similar. That proves the efficiency of the proposed algorithm.

These small substeps introduced a novelty in an entire development process for all aero shapes components, increasing data translation and inspection accuracy. Complex machines like gas turbines or aero engines contain hundreds of parts. Every slight improvement could have a significant meaning for the entire process. That philosophy has a one-goal – continuous improvement. Different names over the globe can be highlighted like “Kaizen,” “Lean,” or “Six Sigma.”

6.2. Further research

Proposed methods for sure improve many technical difficulties, but many more things can still be investigated in the future:

The commercial standard for modern CAD Data Exchange in general [update for ISO standard]: The standards defined globally are not set yet to cover all production-inspection purposes. Primary rules are set locally within specific companies to maintain proper data flow. There is a big field to simplify and standardize data translation globally to adapt to modern machines' capabilities.

Improvements in CAD shape optimization based on mathematical continuities: CAD systems developed nowadays are written for efficient visualization. With the constant hardware development, now is a time to introduce higher math equations for smoother aero shape visualization, starting from the C3 requirement. That would not only affect turbine components but even the automotive and space industry.

An improved commercial filter to delete or blur manufacturing differences compared to an original CAD model shape: All custom filters are written to improve smaller steps of the inspection process and can benefit the entire industry. It is an observed trend that academic researches are willingly implemented in commercial usage and software. It is only a matter of time when additional data filtering will be implemented in the following software updates.

3D printing technology introduced to supersede the casting process: The casting process is a complicated and expensive method that is not intended for small batch production. 3D printing has two potential benefits: tiny, even unitary usage and quick implementation for even mass production. These advantages need to be taken into consideration for future development. If the current limitation of materials used for printing will be solved, such a method would be a great manufacturing alternative. We can see already some industrial investments, and many components can already be 3D printed.

Inspection method for internal (hidden) surfaces to add into a 3D scan file (extension of an X-ray technique to add digital outputs): The main disadvantage for both CMM and 3D scan methods is their limitation to external or open surfaces only. The big challenge for a full inspection is to verify internal (hidden) shapes. There are methods like eddy current testing or X-ray techniques, but this inspection does not involve 3D visualization. There is a large area of research capabilities.

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