ABSTRACT
During on-wing time of a jet engine deterioration occurs and leads to decreasing component efficiencies. This results in increasing Exhaust Gas Temperature (EGT) and Specific Fuel Consumption (SFC). Thereby, the condition of the High Pressure Compressor (HPC) has a comparatively large influence on these parameters defining overall engine performance. This can be explained by a changing flow field in the HPC due to geometric deviations which may occur during operation. The geometries are influenced by erosion which results in thinner airfoils, changed leading- and trailing edge geometries, shortened airfoils and increasing tip clearance.

The objective for future maintenance strategies is to determine the influence of the different wear mechanisms. This can be done by experiments and Computational Fluid Dynamics (CFD). Because of the high number of different mechanisms and locations of deterioration, CFD-calculations seem to be necessary to give a detailed view of the influence of deterioration. In this regard, the following paper will present a developed procedure for analyzing, manipulating and meshing HPC-blades to simulate their flow. Therefore, three different software-routines for the mentioned steps will be shown and explained.

Additionally, an example blade will pass through the process and will be manipulated for max. deviation caused by deterioration. At the end, a CFD-calculation of these blades will be carried out and analyzed for its aerodynamic behavior.

NOMENCLATURE

| Symbol | Description                           |
|--------|---------------------------------------|
| n      | Rotational Speed of N2                |
| p      | Pressure                              |
| p_t    | Total Pressure                        |
| r_{LE} | Leading Edge Radius                   |
| r_{TE} | Trailing Edge Radius                  |
| T_t    | Total Temperature                     |
| t_{LE} | Leading Edge Thickness                |
| t_{max}| Max. Profile Thickness                |
| T_{TE} | Trailing Edge Thickness               |
| V_{Ax} | Axial Velocity                        |
| y^+    | Dimensionless Wall Distance           |
| α      | Absolut Circumferential Flow Angle    |
| β      | Absolut Radial Flow Angle             |
| η_t   | Isentropic Efficiency                 |
| e      | Pressure Coefficient                  |
| κ      | Isentropic Exponent                   |
| λ      | Stagger Angle                         |
| ϕ      | Flow Coefficient                      |
| π_{pr} | Pressure Rise                         |
| τ_t    | Temperature Rise                      |
| ψ      | Work Coefficient                      |
| ω      | Dissipation Rate per Unit of TKE      |

INTRODUCTION
The HPC of a civil jet engine has a strong influence to its overall efficiency. Because of deterioration, the HPC loses performance and efficiency over its operation time, which leads to a decreasing engine performance. To ensure a constant thrust, the engine control will increase the fuel flow, resulting in an increasing SFC and EGT. Upon reaching a defined EGT limit, the engine has to be overhauled to prevent an excessive occurrence of over-temperature events.

At the beginning of the overhaul process, the ex-service blades will be appraised and classified in serviceable, repairable and non-repairable. The former ones are cleaned and get no further treatment other than polishing, whereby the latter ones are to be discarded. Repairable blades can be recycled, for example by build-up welding and recontouring the tip or leading- and trailing edges.

At the end of the overhaul, repaired, new and non-repaired blades are aligned at random across the circumference. Thereby, these different geometries will influence each other and their flow. So, the detailed knowledge of the combinations of different geometries, the achieved efficiencies and surge limits is of great interest.
To determine the possible deterioration levels, Marx et al. [8] analyzed the geometries of two complete jet engine HPC bladeings. In doing so, the blades were digitized by a structured-light 3D scanner in conjunction with a photogrammetric system. Afterwards, the measured point clouds were analyzed on different blade heights for their geometric properties, such as stagger angle and a variety of thickness-related parameters. To determine manufacturing tolerances, Marx analyzed 300 new blades in equal measure. Marx could show higher deviations caused by operational effects than manufacturing tolerances. He figured out a decreasing leading edge thickness of 25% in a front stage and an increasing leading edge thickness of 40% in the aft stage referenced to the new blade values. Furthermore, he could show changes in stagger angle up to $\pm 1^\circ$.

Based on Marx’ results, Reitz et al. [11] analyzed the behavior of deteriorated HPC blades. The objective of his research was to order different deterioration effects independently from each other. Therefore, three deterioration effects were investigated: Changes in leading edge thickness, max. profile thickness and stagger angle. These deterioration effects have been generated in different strengths. The range of change was given by Marx’ results and covered the spread of determined deterioration. For the blade generation an internal software was used, which allowed an independent change of geometric properties. As a result, noticeable effects on stage performance caused by deterioration could be shown. Thereby, the changes of leading edge thickness had the highest impact, followed by max. profile thickness and stagger angle.

Further investigations have been done by Krone et al. [5], who analyzed the influence of deterioration on the efficiency of a HPC. Krone investigated a new, two deteriorated and a repaired blade of a HPC mid stage. Even though the changes in leading edge thickness are smaller than those identified by Marx, the influence on performance is noticeable. A full blading with identical setup leads to a performance an internal software was used, which allowed an independent change of geometric properties. As a result, noticeable effects on stage performance caused by deterioration could be shown. Thereby, the changes of leading edge thickness had the highest impact, followed by max. profile thickness and stagger angle.

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Kellersmann et al. [4] analyzed deterioration effects of a blade integrated disk (BLISK), where blades cannot be rearranged during overhaul. Thereby, his researches focused on the interactions between blades changed in stagger angle and leading edge thickness. He confirms the trends found out by Reitz [11]. In addition, an interdependency of deterioration effects could be observed. At high flow coefficients, the throttle lines of the coupled deterioration effects lay in between their standalone ones. Nevertheless, the stagger angle shows a higher influence at low flow coefficients, caused by the closing and opening of the cascade.

Further investigations to compressor deterioration have been done by Tabakoff et al. [13], who showed an increase in SFC of 0.38% caused by blunted leading edges and additional 0.13% caused by a higher surface roughness. The high influence of leading edge geometry to blade performance could also be shown by Giebmanns et al. [3]. She compared blades with blunted leading edges; blunted leading edges and shortened chord length; reduced chord length with reshaped leading edges. Thereby, she determined the leading edge geometry as a main factor for stage performance, because a properly reshaped but shortened blade showed a comparable behavior as the new one. Such a blade was found to perform unfavourably only in terms of stability (surge margin).

The aerodynamic influence of fan blades damaged by foreign object damage (FOD) was investigated by Bohari et al. [2]. Therefore, Bohari changed the geometry of one blade in row by rotating its leading edge. A followed CFD-simulation for three different rotational speeds showed the impact of the damage to fan performance: The changes of pressure rise and mass flow rates were negligible. Nevertheless, a significantly influence on stall margin could be noticed. The stall margin was decreasing at all rotational speeds for the damaged blade.

Summarized, a multitude of investigations has been carried out in the area of compressor deterioration. Nevertheless, an accurate knowledge of changed stage performance caused by different geometrically deteriorations and their aerodynamic interaction is not available. In order to fill this knowledge gap, a semi-automated process of generating deteriorated digital blades, meshing them and performing CFD-calculations is necessary. This process would allow for analyses of a wide range of geometric deviations, as it could cover the whole range of realistically deteriorated blades in a jet engine compressor.

Such a process will be presented and demonstrated in this paper. In the first part, the designed software modules are shown. They comprise an analyzer, modifier and a meshing tool. The second part of the paper includes a demonstration and the CFD-results of an example geometry.

SOFTWARE MODULES

The presented process can be split up into four sub-routines. The first one is the Analyzer, which evaluates a given point cloud of a blade. This point cloud can be provided by a structured-light 3D scanner in conjunction with a photogrammetric system. With the Analyzer it is possible to extract the geometric informations of the selected blade. Additionally, the Analyzer provides the necessary input data for a reference-blade-model in the following subroutine: The Modifer. With the Modifer it is possible to manipulate the reference geometry to simulate different deterioration effects. Thus, no physical blade is necessary to investigate different blade geometries. The Modifer provides the geometry for the following Meshing. This subroutine generates scripts for the meshing-tool Au-togrid from NUMECA. These scripts are created and adapted to the present case, so that effects like bleeds and cavities can be meshed or not. The generated mesh is the input for the following CFD-calculations, done by TRACE [1] [6] [9] [10]. At the end, the CFD-results can be analyzed e.g. throttle lines or exit flows.

Analyzer

The first sub-routine in the presented process is the Analyzer. The Analyzer is able to evaluate the geometric properties of a 3D-point cloud or just of a 2D-profile. In the presented case, a 3D-point cloud is given. For the analyzed HPC stages, the Analyzer ensures the right point cloud orientation with an integrated alignment algorithm. Therefore, the alignment algorithm uses the blade root to orientate the blade in space.

![Fig.1 Interpolation of profile points](image)

Now, the Analyzer places cones on the wished heights through the 3D-point cloud and projects the surrounding points on the cones. These cones are representing streamlines through the channel. The extracted points form the profile, but are still in disorder and show a high inhomogeneity in their distribution. A process is necessary to sort the points clockwise to each other. Additionally, the process ensures a maximum distance from one point to its neighbour for a homogeneous point distribution. Is the distance higher than...
allowed, new points were fitted with an interpolation into the gap (see FIG. 1). Now, the data has the right format and point density, to start the actual analysis of the profile.

First, circles were fitted into the edges to get the leading and trailing edge radii. It is a simplified process, because the deteriorated geometry will not have an ideal round edge. A deeper look on the edges will be done later in the process. There, the stretching, asymmetry and metal angle of the leading and trailing edges will be calculated. After fitting circles in the edges, the profile is grossly cut into the pressure and suction side. Following, on each point of the pressure side, a circle is set and enlarged until it reaches the suction side (rolling-ball-method). The midpoints of the circles form the mean line of the profile (see FIG. 2). To identify the leading and trailing edge point, the mean line has to be extended, until it cuts the profile at its ends. This is done by a sixth order fitting curve through the circle midpoints. The gradient of the curve at the leading and trailing edge point is the metal angle at leading and trailing edge. The chord is defined as the closest connection of leading and trailing edge point. The angle between chord and machine axis is called stagger angle. The distance between chord and circle-midpoints is defined as camber and the diameter of the circles results in the thickness distribution. Figure 3 shows a simplified definition of some geometric parameters. However, more parameters are analyzed, such as center of gravity, edge asymmetry and stretching. Additionally, blade specific parameters like blade height can be calculated, too.

At the end of the analysis, the Analyzer returns the results in an appropriate format for further statistical analysis. Furthermore, the Analyzer provides the input data for the following Modifier. With the Modifier, a reference geometry will be distorted to simulate different deterioration effects and levels. For this purpose a suitable reference geometry is necessary. Because of this, it is reasonable to use a new part as reference for following blade-modifications.

**Modifier**

Previous publications already addressed parameter based compressor blade models (see [7]). Lange et al. developed an algorithm to reproduce geometric differences caused by manufacturing tolerances. In contrast, the Modifier is able to alter and distort the geometry of a reference blade to simulate different deterioration effects. Therefore, the geometry data set has to be provided by the Analyzer, explained above. It is possible to manipulate the geometric properties independently or in conjunction, so each deterioration combination can be simulated, without having a physical component. During the airfoil modification, profiles in 5% duct height distances were generated and aligned together to a 3D-airfoil model.

The first step of the Modifier is forming the chord and turning it on the desired stagger angle. Subsequently, the camber distribution has to be distorted, to fulfill the specified requirements. The user can define new metal angles at leading and trailing edge, the max. camber and its position (see FIG. 4). Afterwards, the camber distribution is added to the chord to get the new mean line. The final profile is created by adding the thickness distribution to the mean line. The thickness distribution can be distorted as well as the camber distribution. Thereby, leading and trailing edge radii and thicknesses as well as maximum profile thickness and its chordwise position can be manipulated (see FIG. 4). Giebmanns et al. [3] showed the strong impact of edge geometry. In order to meet these requirements, the edge geometry is defined by five parameters: Radius, thickness, stretching, asymmetry and metal angle.

After finishing the 2D-profiles, the Modifier aligns each profile by a chosen alignment method (e.g. by its center of gravity and a stored stacking line). At the end, a 3D-airfoil model is generated with evenly distributed points over the profiles and a higher resolution at the edges (see FIG. 5 a). Figure 5 b shows the deviation between the reference blade and its replica. As can be seen, most of the airfoil has deviations below 25µm. The area averaged deviations are 6µm. Thus, they are of the same order as measuring accuracy of the structured-light 3D scanner.
A further example for the flexibility of the presented process is shown in FIG. 6, where a FOD was reproduced. In order to investigate the performance after a possible repair, a blending was done. As can be seen, a wide area in tip range was repaired by blending the blade. Additionally, the blade has a bump in this region, caused by changed stagger angles.

The meshing-tool Autogrid is used for the following meshing of the geometry. Autogrid requires airfoils, which intersect with the hub and shroud contour. So, the Modifier delivers extended airfoils and the final blade height and, therefore, tip clearances are adjusted during the meshing process. Additionally, geometric properties like fillets or partial gaps are included during the meshing, too.

SIMULATION SETUP

In the presented test case, a HPC front stage of a civil jet engine, consisting of rotor and stator row has been chosen. For the simulations, just the rotor with its geometric properties has been changed in different deterioration levels. Subsequently, these deterioration levels have been paired with a stator blade, representing a new part.

To determine the range of geometric changes, 120 blades of the chosen stage have been measured and analyzed. Afterwards, representative geometric properties of a blade with minimal, maximal and mean values have been generated. Of course, possible correlations between some parameters like edge parameters, have been taken into consideration to achieve the most accurate result. Finally, the rotors were created by varying leading edge geometry, stagger angle, chord length, profile camber and thickness.

The variances for chosen parameters are shown in FIG. 7. The plot shows deviations of leading edge thickness $t_{LE}$ and stagger angle $\lambda$ referenced to a new blade (black vertical line). As can be seen, blade $\text{min}$ has an approx. $20\%$ thinner airfoil compared to the new blade. Blade $\text{max}$ has nearly reference thickness, except for the tip region, where its leading edge thickness is approx. $20\%$ higher. The values of blade $\text{mean}$ are located in the middle of blade $\text{min}$ and blade $\text{max}$. The stagger angle of blade $\text{min}$ is approx. $0.5^\circ$ smaller than reference. In hub region blade $\text{max}$ has a $0.25^\circ$ higher stagger angle than the new blade and in tip region about $0.5^\circ$. Additionally, blade $\text{min}$ has sharper edges than the new blade and blade $\text{max}$ has blunted edges.
properties are the total pressure radial distributions of the flow properties were extracted. These HPC stages and bleed ports. On the corresponding interfaces, the full HPC calculation includes the whole compressor geometries like in a conventional civil jet engine with medium thrust class. This calculation with design blade geometry. The compressor is installed responding inlet distributions were extracted from a full HPC calculation with design blade geometry. The compressor is installed.

Please take note that some deterioration effects, like roughness or changing tip clearances, have not been taken into account. The rotor and stator tip clearances were adjusted to 1% channel height. Additionally, fillets have been added during the meshing.

Now, the geometries went through the meshing process. The result of the meshing process is a one pitch periodic mesh for rotor and stator geometries (see FIG. 9). In the CFD-calculations, the circumferential speed \( U \) over circumferential speed \( \psi \) combines the total temperature rise and the circumferential speed \( U \):

\[
\psi = \frac{2 \cdot c_p(T_{t3} - T_{t1})}{U^2}
\]

The pressure coefficient \( \varepsilon \) is defined as product of work coefficient \( \psi \) and isentropic efficiency \( \eta_{is} \):

\[
\varepsilon = \psi \cdot \eta_{is}
\]

Thereby, the isentropic efficiency \( \eta_{is} \) can be calculated by the total to total pressure rise \( \pi_{tt} \)

\[
\pi_{tt} = \frac{p_{t3}}{p_{t1}}
\]

and the total to total temperature rise \( \tau_{tt} \)

\[
\tau_{tt} = \frac{T_{t3}}{T_{t1}}
\]

with following equation.

\[
\eta_{is} = \frac{\psi_{max} - \psi_{min}}{\pi_{tt} - 1}
\]
Please note, that the operating point with lowest flow coefficient does not represent the physical point of stall. With a steady state CFD-calculation it is not possible to determine the exact point of stall with its instationary behavior. The operating point with lowest flow coefficient is just the last converged solution. A further reduction in mass flow did not lead to a converged solution.

Figure 10 shows the work coefficients of the simulated stage. The black vertical dotted line represents the ref. flow coefficient for the HPC design point. First of all, it can be mentioned, that geometric changes caused by deterioration result in noticeable changes in stage performance. It can be seen, that blade_{max} delivers nearly the same work coefficient as the new blade. Both graphs are on top of each other. This can be explained by the small geometric difference of both blades. The only difference is the earlier blocking of blade_{max} caused by the little thicker airfoil. The thicker airfoil has a stronger acceleration and reaches the Mach Number of one over the whole passage earlier than the new blade.

However, the situation appears to be different for blade_{mean} and blade_{min}. Here, the work coefficients show noticeable differences to the new blade over the whole range. This is caused by the higher discrepancies between the geometric properties, compared to blade_{max}. Thereby, the work coefficients seem to be positively influenced by deterioration and are increasing. Because of the decreasing stagger angle, the curves are shifted towards lower loadings. For blade_{min} this shifting leads to an earlier stall, represented by an earlier divergence of the calculation. Furthermore, blade_{mean} and blade_{min} have a weaker acceleration compared to the new blade and reach choking condition at higher mass flows.

Figure 11 presents the pressure coefficients of the simulated stage. Similar to the work coefficients, the pressure coefficients show noticeable changes caused by deterioration. Again, the black vertical dotted line represents the ref. flow coefficient for the HPC design point. It should be remembered, that the pressure coefficient is the product of work coefficient $\psi$ and the isentropic efficiency $\eta_{is}$. So, the pressure coefficient represents the efficiency of the stage. It can be seen, that blade_{max} shows a decreased pressure coefficient over the whole range. In contrast, blade_{mean} and blade_{min} have increased pressure coefficients. Comparable with work coefficients, the pressure coefficients show an offset towards lower loadings with decreasing geometric values as stagger angle. Nevertheless, peak efficiency of blade_{min}, i.e. maximum deterioration, shows higher values.

To give an answer to the question why deterioration can result in higher efficiencies, the contour plot in FIG. 12 illustrates the difference between the Mach Number distributions of blade_{min} and blade_{max}. The contour plot shows a profile in blade tip range and, therefore, a transonic flow regime. The chosen operating point is at peak efficiency mass flow of the new blade. Because of the chosen rotational speed and inlet temperature, respectively, no shock is present. Blade_{min} has a higher averaged deceleration than blade_{max} ($\Delta \text{Ma} < 0$). Only near leading edge, blade_{max} shows a higher acceleration. The higher deceleration of blade_{min} is in accordance with its higher work coefficient $\psi$. Additionally, the increased Mach Number distribution, especially in mid-passage, of blade_{max} confirms the prior explanation of its earlier blocking.
Table 2 summarizes the deviations between operating points, representing respective peak efficiency, for work and pressure coefficients and isentropic efficiency. The given values are referenced to the new blade. Even though blade \( \min \) has a higher value of peak efficiency than the new blade, the associated pressure coefficient \( \varepsilon \) is lower. This can be explained by the curve shifting towards lower loadings and, therefore, lower pressure ratios at peak efficiency. So, the product of work coefficient \( \psi \) and isentropic efficiency \( \eta_{is} \) is decreasing.

Table 2 Analysis of changes in performance for front stage blade geometry deviations, extracted from single stage calculations

| Variant | \( \Delta \varphi \) | \( \Delta \psi \) | \( \Delta \varepsilon \) | \( \Delta \eta_{is} \) |
|---------|-----------------|-----------------|-----------------|-----------------|
| Min     | 0.016           | -0.61           | -0.16           | 0.40            |
| Mean    | 0.005           | 0.64            | 0.68            | 0.03            |
| Max     | -0.001          | 0.48            | -0.05           | -0.45           |

Overall Compressor Performance

Further calculations shall evaluate the influence of a deteriorated front stage for the entire compressor. Therefore, the analyzed front stage variations, shown in the section above, have been integrated into the full compressor model. This model is equal to the model of boundary condition extraction and includes all compressor rows, bleed ports, etc. Besides the front stage variations, the model consists of a newly blading. Because of the model dimensions, just one operating point for each deterioration level was calculated. This operating point represents cruise condition and is illustrated in FIGs. 10 and 11. Thus, table 3 shows the aerodynamic performance of the HPC design point, illustrated by the black vertical dotted line in FIGs. 10 and 11. Therefore, a single stage was calculated separately. The changes of the front stage aerodynamic performance can be observed in the full HPC calculation, as well.

Table 3 Analysis of changes in performance for front stage blade geometry deviations, extracted from full HPC calculations

| Variant | \( \Delta \varphi \) | \( \Delta \psi \) | \( \Delta \varepsilon \) | \( \Delta \eta_{is} \) |
|---------|-----------------|-----------------|-----------------|-----------------|
| Min     | 0.001           | 1.55            | 0.64            | -0.76           |
| Mean    | 0.000           | 1.08            | 0.62            | -0.39           |
| Max     | -0.001          | 0.36            | -0.09           | -0.38           |

Table 4 analyzes the deviations of the full HPC aerodynamic performance between the calculated deterioration levels. Even though only the front stage of the compressor has been systematically altered, its influence on overall work coefficient \( \psi \) of the HPC can be easily noticed. The negligible change of flow coefficient \( \varphi \), or massflow, indicates that the deviations are not evoked by changing the throttling of the compressor. Furthermore, the compressor shows changes in efficiency: Although the work coefficient \( \psi \) is increasing, the pressure coefficient \( \varepsilon \) is not changing. Consequently, the isentropic efficiency \( \eta_{is} \) has to be decreased.

Table 4 Analysis of changes of overall compressor performance caused by a varied front stage

| Variant | \( \Delta \varphi \) | \( \Delta \psi \) | \( \Delta \varepsilon \) | \( \Delta \eta_{is} \) |
|---------|-----------------|-----------------|-----------------|-----------------|
| Min     | 0.000           | 0.26            | -0.01           | -0.21           |
| Mean    | 0.000           | 0.14            | 0.00            | -0.11           |
| Max     | 0.000           | 0.12            | -0.01           | -0.10           |

CONCLUSIONS

In this paper, a process for analyzing, manipulating and meshing of deteriorated compressor blades was shown and demonstrated with an example blade geometry. The chosen example was a HPC front stage of a modern civil jet engine. Its geometry was digitized by a structured-light 3D scanner in conjunction with a photogrammetric system. The obtained point cloud was analyzed for its geometric properties, such as thickness distribution and stagger angle. The extracted information is subsequently distorted and composed to an artificially deteriorated blade. Thereby, the geometric values of the composed rotor blades represent typical geometric changes caused by jet engine deterioration. The next algorithm creates and provides the scripts for the meshing tool Autogrid. Then, CFD calculations were realized with TRACE. The complete process chain can be briefly summarized as follows:

1. Digitized airfoils can be analyzed for their geometric properties by the presented software.
2. The software is able to create any artificially deteriorated airfoils by manipulating the geometry of a reference blade.
3. A downstream process creates and provides the scripts for a fully automatic meshing of the geometry.
4. The performance map is automatically calculated by TRACE.

At the end, the CFD-results have to be analyzed. In the presented case, three different deterioration levels have been compared to a new blading. Therefore, a single stage was calculated as well as the entire HPC. The chosen rotational speed and entry boundary conditions are representing cruise condition. The results of single stage calculations can be summarized as follows:

1. Deterioration induces noticeable changes in stage performance.
2. Changing stagger angles result in a shifting of characteristic curves.
3. Blade \( \text{blade}_{\min} \) has comparable geometric properties as the new blade. So, the pressure and work coefficient is equal over a wide operation range. Just at low loadings the curves fan out. This can be explained by slightly increased thicknesses which result in an earlier blocking of the passage.
4. Blade \( \text{blade}_{\text{mean}} \) and blade \( \text{blade}_{\max} \) show an increased averaged deceleration, which results in higher peak efficiencies.

Additionally, the influence of a deteriorated front stage on overall HPC performance has been assessed. The shear size of the model, however, only allowed for a single operating point calculation per deterioration variant. Therefore, the cruise condition was chosen. The results can be summarized as follows:

According to expectations, deterioration of a front stage rotor influences the behavior of the entire HPC. However, while the work coefficient shows a noticeable response to the evaluated geometry changes, their impact on pressure coefficient is negligible.
It has to be mentioned, that some deterioration effects like roughness or changing tip clearances have not been regarded.

For a yet deeper understanding of the influence of blade deterioration on compressor performance some further actions have to be done in future studies:

1. Further studies should also address changed roughnesses or tip clearances.

2. To fill the parameter space of geometric properties, a design of experiments should be carried out. Thereby, further geometries with random geometric properties could be calculated to identify the range of variation of characteristic curves.

3. Additionally, deterioration of stator vanes should be taken into account.

4. At an advanced stage, deterioration of the entire machine should be analyzed. In doing so, a prediction of the entire jet engine could be given, depending on HPC condition.

The next step should be the design of experiments to fill the parameter space of an entire stage. Therefore, the tip clearance should be taken into account as well as changed stator vanes. By this means, the range of characteristic lines could be characterized for a single stage. Further studies could check if the received range of characteristic lines is applicable for the other stages or if the same work has to be done for every single stage.

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