A Parametric Blade Design System (Part I + II)

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Abstract

A complete 3-D Parametric Blade geometry design system for industrial design project applications is presented.
The system generates a 3-D free-form surface of an axial compressor or turbine blade by means of individual definition of quasi 2-D stream surface blade profiles.
These profiles are then stacked relative to a reference point for each section along a so-called "stacking line".
All design properties both for the quasi-2-D profiles and the 3-D stacking line are parametrised in a problem-adapted way to support the understanding of the aerodynamic engineer. These parameters are then transformed into a fully CAD-compatible B-spline representation.
The geometry engine is completed with a CFD-code integration, a blade profile optimising package, a parametric database and a correlation utility to find good starting solutions for new design tasks based on existing proven technology.

Abbildung 1 BR715 Turbine Blades

The complete design systems offers a number of project-related advantages to the user: the system is fully integrated into the complex engineering design process for turbomachinery modules like a multistage compressor or turbine.
It offers a bi-directional data exchange between different design disciplines such as stress & mechanical analysis, aerodynamics, checking of mechanical constraints, thermal analysis and CAD-design for platform, root, shrouds etc.
The system is completed with optimisation strategies based on parametric free-form-solids generation. It is linked to an engineering database and into an EDM/PDM system.

To support preliminary design activities in an early stage of a design project the system contains a correlation utility to interfere from existing designs and get a reasonable initial multistage design blading for a compressor or turbine.

The presentation will be splitted in two parts:

Part I

1. Introduction
2. Basic Principles of the design task
3. Outline on the major system components
4. Experiences with industrial applications
5. Parametric 3-D blade manipulations
6. Recommendations

Part II

1. Technical Details: geometry representation, optimisation, correlation rules, parametric stacking
2. Curvature distribution
3. Standard profile properties
4. Cloning
5. System integration
6. Profile editor **b2d**
7. Implementation details
8. Graphical user interface
9. Integration into CAD/CAE environment
10. General remarks

Abbildung 2 The new Boing717 twinjet with BR715 engines

Introduction

Blade design & gas turbine business

The gas turbine business has changed over the last five to ten years. In the seventies and eighties a large number of physics-based technology programs were carried out, especially in the aero/thermo and acoustics area. These programs all together have led to an essential reduction of SFC and hence improved the cost situation for the airlines. In the nineties engine maker have put more emphasis on cost and quality issues. The common core family concept of the BR700 engine family is one successful example of an innovative technical approach to tackle both engine development costs, time and quality for a number of similar derivative products with a significant amount of common components.

On the other hand the cost competition has gradually changed into a time- and innovation competition (time based competition). Every player in the global aeroengines market is trying to find and strengthen its unique selling proposition to stay in the market and make profit with reduced time-to-market and innovative engine concepts.

The main condition for that is for a single company to be able to design and certify the right engine at the right time for the right application. Technology is still very important and will be developed. But with limited resources, companies must re-think the cost benefit of certain purely physics-based research programs of the past because further return of investment will be quite low. „High tech“ as the one and only *unique selling proposition (USP)* is not enough for today’s customers, they assume it and demand reduced costs for the product as well.

That’s why companies have to focus efforts and technology programs on those things that impact units cost most: reduction of hardware costs, design & re-design costs and reduction of expensive test series by numerical simulation and concurrent simultaneous engineering.

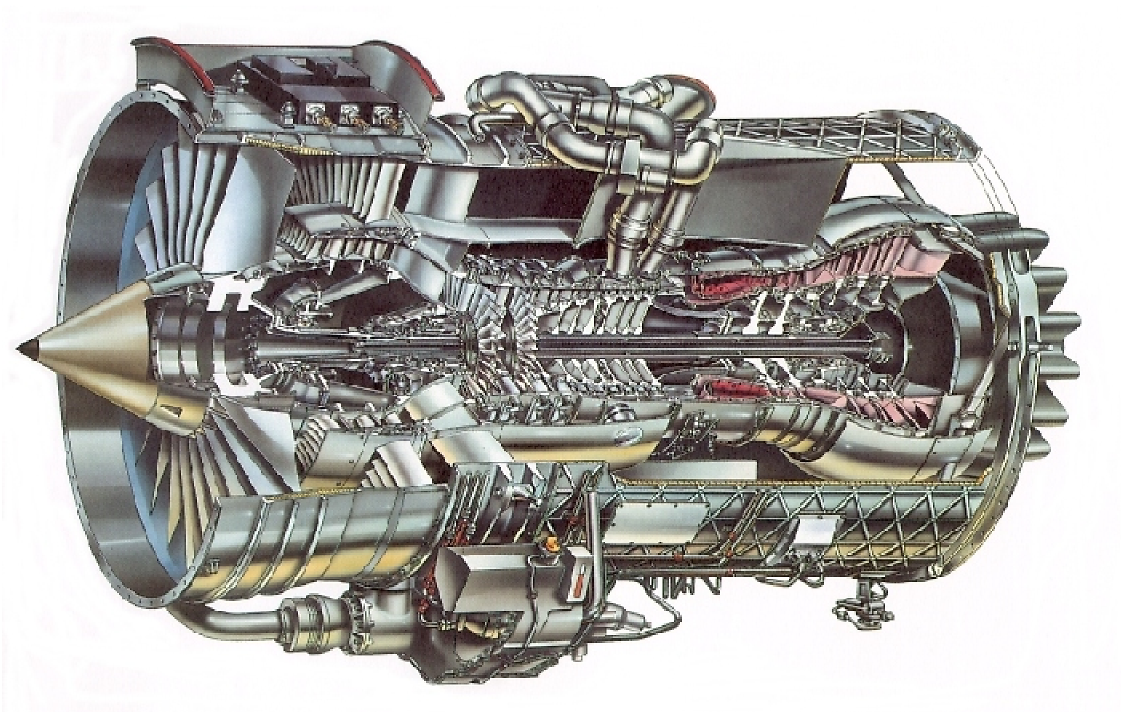


Abbildung 3 The dressed BR715 engine

One way to proceed is improvements of methods in the engineering development areas. The objective is to improve the engineering design process, which to a large extend now is computer based. Concurrent simultaneous engineering is the key word for these activities in the past. The complex blade design process is one major part of that.

CAD developments

The design process in aeroengine design is fundamentally driven by physical properties of the components, it’s weight, performance, stress behaviour and life. All these properties are estimated by various numerical simulation methods such as FEM, CFD and crack propagation calculations.
On the design side engineers are using more and more advanced CAD system features. Originally the CAD was just a replacement of the drawing board to get 2-D sketches out rapidly and with the chance to correct without starting from scratch. Then the 3-D CAD systems came up where designers could create and combine standard geometric entities such as cylinders, cubes, tetrahedra, sphere and free-form surfaces. Then more and more emphasis was put onto processing the topological information of a part or assembly. People started generating „watertight“ solid models in CAD. Geometric library standards were established such as ACIS, Parasolids and STEP to uniquely describe functions and properties of the geometric representation of a solid part.
In order to process iterative changes and adjustments of a given part without changing topology *parametric* CAD systems were developed. The idea of introducing parametrics into CAD revolutionised the design work and a new level of efficiency in CAD work could be reached. The parametric idea was so important to the CAD community that one of the pioneers and market leaders in this business decided to name themselves „Parametric technology Corporation“.
Now with parametric 3-D solids as a standard, the original work of step-by-step developing the CAD part and creating sketches, drawings and views is more and more loosing its importance in the whole development cycle. Parameters of a topological „master model“ can be treated outside the CAD world and can be subject to optimising processes or application of artificial intelligence, neuronal networks, expert and decision support systems.
Once the master model is generated, the job of finally generating the solid model and all required drawings and views is just a matter of pressing a single button. After a final optimised parametric configuration has been detected, the parameter set is passed to the CAD and replaces the generic parameters of the „master model“ to create the final model.

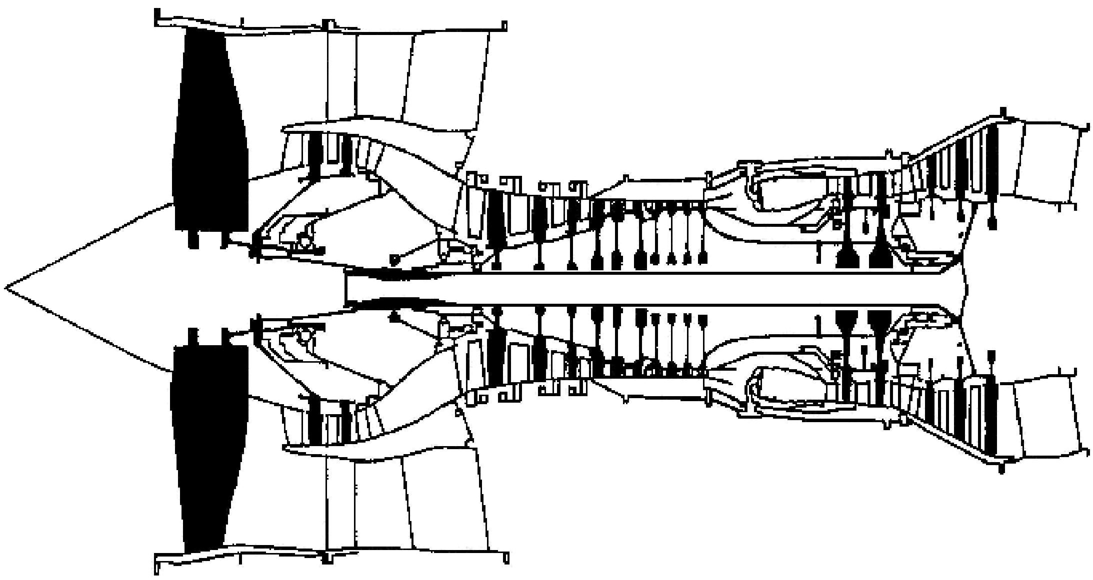


Abbildung 4 Sketch of the BR715 engine

In the typical business of an aeroengine company the number of major different „master model“ parts is fairly restricted and will not change so frequently. This is basically the turbine & compressor blades with their respective platforms and feet - only a limited number of different

designs is in common use today - , discs, shrouds, drums, sealings and the annular combustor - just to name the most important parts of a core engine. Once a library of all relevant master model parts is created, future designs will largely consist of recombination, adjustment and small incremental improvements of these fundamental entities. This process is driven by engine specifications and numerical simulations of the aero/thermal performance and other objectives.
So we end up with an engineering process were design and simulation are very much integrated. Bidirectional data exchange between the different simulation models and the CAD is essential. Also meshing of the models or their respective surrounding volumes (for CFD) is essential. It is vital for that process to use geometric standards like ACIS, Parasolids, STEP or IGES for the model descriptions throughout the whole system.
Most commercial meshing, CFD and FEM tools have interfaces serving to these standards. We need to make sure that also the CAD and the other parts of the process are using the same standards.

Aerodynamic blade design process

The blade geometry design process generally plays an important rule in the development and verification of a new gas turbine or aeroengine. It is the inner loop of most design iterations and hence - taking into account the high number of different blades required for a multistage compressor or turbine - is a critical cost factor for the task.
However, from it’s very nature it is a seasons’s job and in many aspects not very attractive to the scientific community in this area. The limited number of recent publications in the field and the fact that very often students and young engineers are given the ugly job to create the topologically all-so-simple geometry speak a clear language. But is it really so simple?

Aerodynamic design deals with boundary layers, shock losses, secondary flow patterns, surface curvature distributions, blade metal and air angles like wedge, inlet & exit angle, stagger & camber. In the early years of aerodynamics standard profile families were developed like NACA in order to describe the profile with a small number of parameters and be able to compare designs and test results of different aerodynamic shapes.
Later on the aerodynamisits learned more about the physical effects of boundary layer separations, turbulence, reattachment, skin friction and shape factors and nonsteady loss generating mechanisms. As a consequence of that a new style of optimised compressor blades came up, the so called controlled diffusion aerofoils (CDA). The CDA profile philosophy is mainly based on the understanding of the suction side profile boundary layer physics. The CDA profiles have extended the design space for the blade geometry virtually to infinity.
In the low pressure turbine area people realised the positive effect of calming for the stability of the boundary layer and increased blade loading, simply took off up to 20% of the blades out of a single bladerow.

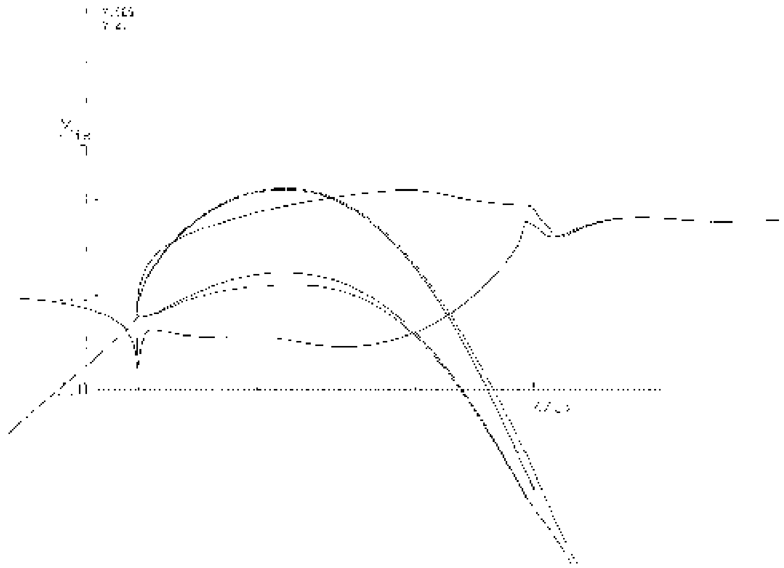


Abbildung 5 Aerodynamic performance prediction for LP turbine blade section

Inverse design methods where developed in which engineers start from an optimal surface pressure distribution and try to generate the accompanying blade profile which creates the desired pressure distribution.
However, especially the CDA developments stated new requirements to the geometry design process of a compressor blade. In general, standard CAD systems were not suited to meet the requirements of these new CDA design tasks. People in all major aeroengines companies started to develop highly specialised blade geometry design software in order to generate the best possible CDA profiles. Design space simply exploded to huge dimensions. Every single section out of 20 or more on different radial positions for a single blade in a 10 or more staged compressor with 20 or more bladerows was individually designed to the objectives of the CDA design rules. In all these individual Blade design software systems each individual blade section had usually more than 200 degrees of freedom. Companies started to view this technology as core competence and invested a lot of effort to develop and maintain these highly complex software systems. They were usually backed up with numerous strategies to stack the set of 2-D sections over different height to a complete 3-D blade in a smooth and aerodynamically efficient way. Most 2-D base systems were actually designing the profiles on so-called stream surfaces (surfaces of revolution with the assumption that circumferentially averaged normal flow vectors vanish). This puts an extra difficulty into the geometry design software.

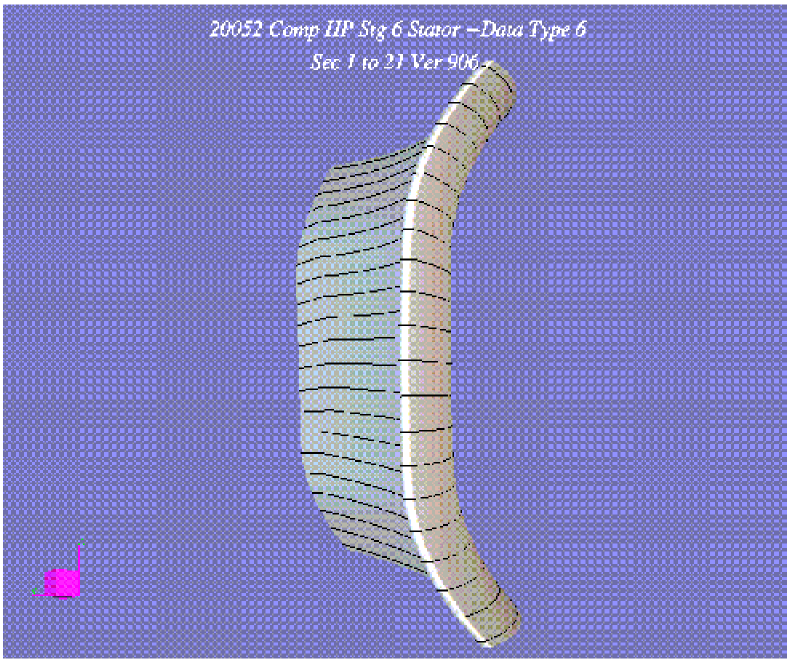


Abbildung 6 Stator blade with stream sections and bowed hub and tip region

Also, systems were coupled with 2-D flow solvers to interactively simulate the flow and improve the design.
With all that in hand the design task for a 10stage compressor became a nightmare. The systems offered all kinds of options and even the most odd design idea could be created. The systems were really at an endpoint were they could do everything for you but it was simply too much. Users very often got lost in the enormous design space dimensions and the effort to improve a given design did very often not compare well to the technical benefit of the improvement. Also people developed individual different design strategies to work with these systems leading to very similar designs on completely different ways.

This has led to the question wether the approach of „total design space“ was not suitable for an efficient process. Would it be better to limit the degrees of fredom for the blade design to a reasonable number, i.e. specify the design space as large as necessary to do what you want and as small as necessary to restrict complexity.

A number of attempts have been made and published dealing with the question of how many parameters are actually needed to design a single section. [cf. /1/,/2/,/7/,/8/,/9/,/10/]
The general outcome of all these research work was that for a compressor blade section 20-22 design parameters should be sufficient with a turbine blade potentially requiring 2-4 parameters more to meet all possible design cases.
A standard way to proceed now was to use a B-spline geometry representation and translate the B-spline parameters 1-to-1 into the language of an aerodynamic engineer.

Now, B-slines is the dialect that most CAD systems can understand. The only task in-between is to transfer the parameters without loss into the 3-D solid CAD world. Some extra work is required to do that, especially when the design works on real stream-surfaces with varying radial height along the axis. The local co-ordinate systems on these stream surfaces can be extremely dangerous, since they are not angle- or distance -preserving, i.e. Pythagoras is not valid, depending on how you define them. So some integration and approximation is necessary in the general case for the data exchange between CAD and aerodynamic design system. But this process is numerically very stable and accurate and does not deteriorate the fundamental principle of bi-directional data exchange between both systems.

Aspects of commercialisation

When the technical problems of non-linear behaviour of physical behaviour and the intractability of the underlying partial differential equations and their relevance to the development and improvement of a technical solution have been detected first, a number of companies started to develop their own expertise in the respective areas.
Later, when in the past decades a number of technologies have reached a high degree of maturity, more and more commercialisation took places and tasks were treated in a standardised way. A number of companies settled down offering technical solutions to the problems, very often a combination of a specialised software package + consulting and training service.
The FEM area is a well known example for that development. From the very start of recognising the problem to the de-facto industrial standard of FEM software solutions and vendors like MSC/Nastran for stress FEM analysis was just 2 or 3 decades. This was back in the Eighties. Since then even competing companies have no problem to work with identical the same software package to simulate and predict the stress of their components. This technology is no longer a *unique selling proposition* for them. It has become a standard.
Now we experience the same concentration and commercialisation of software solutions in the CFD area. Companies like Fluent and NREC (just to name two companies without any attempt to completeness) have reached a very high level of expertise. It is nearly impractical, even for a large aeroengines company with quite specific requirements with respect to the capabilities of the numerical code, to develop and maintain their own CFD software package.
It is economical and for time and development risk reasons much more appropriate to buy a commercial package, integrate it into the company’s engineering process environment and discuss software extensions with the vendor, if necessary.

The question now is whether we will see the same story for the complex of „integrated aerodynamic blade design“ In this area it is also getting very expensive for the aeroengines companies to maintain the required degree of expertise in their in-house developed systems. On the other hand, this technology is more and more not viewed as a core competence for the company. Aspects like the right general arrangement of the engine, family concepts, design for ease of maintenance, design for low cost, design for reliability are playing a much more important role for the chances to make profit.
Thus the technical and economical relevance of a in-house core-competence in advanced blade design has to be reviewed potentially. Taking all that into account it is not unlikely in the future, that the worlds aeroengines industry will have a (presumably small number of 2-3) highly specialised engineering software companies supplying state-of-the-art blade design technology to this industry.
The design software package presented here is viewed to have a degree of maturity to potentially establish a base technology for this task.

The design task

Constraints and design targets

The design of a turbomachinery blade is an iterative process, where a number of (sometimes competing) targets have to be met.

The following is a list of the major design constraints and variables which are checked during the design phase:

Constraints		
Mechanical	**Thermodynamic constraints**	
aerodynamic block - axial positioning of the blade	2-D, quasi 3-D	3-D
annulus definition, curved blade edges axial position	throughflow values	stack (positioning of blade sections along in the radial direction)
torsion and bending modes of the blade	air inlet & exit angles, mach numbers, pressures, temperatures	end bends
life (for turbine blades)	turbulence ratios	
FOD (foreign object damage)	passage area, throat area	endwall treatment
	stagger	3-D blading
	camber	tip leakage flow
	position of maximum thickness	casing & hub treatment
	curvature distribution on suction and pressure side	non-axisymmetric end-walls
	leading edge geometry (circle, ellipse, spline) blade angles	radial smoothing of the blade
	inlet metal angle, exit metal angle	high aspect ratio of surface mesh
	inlet & exit wedge angle	

The BRR parametric blade design system

This chapter gives an overview of the BMW Rolls-Royce **parametric blade design system**.

The **parametric blade design system** is an engineering software package designed at BRR to make the complex compressor & turbine geometry design process

- better
- faster
- more reliable
- standardised.

The introduction of the **parametric blade design system** will influence other related processes, such as FEM- and CFD-analysis and CAD-design.
This has the potential to simplify and improve the whole 3-D blade design process.

The system consist of several modules:

- AutoBlading
- Blade Profile Optimisation
- parametric Blade stacking
- radial Blade smoothing and interpolation
- parametric CAD interface
- parametric database

These modules together form an base prototype of the system.

With the limited resource and time constraints of an industrial company in the aeroengines business it is clearly not possible to implement such a complex system up to the standard of a commercial software product in terms of reliability, easy of use and user interface integration. However, with the application of best software technology and highly specialised external software consultancy for implementation a maximum value software result could be achieved. More work is at hand to test the **parametric blade design system** and integrate it into the design process. This activity has to be driven by the user community within engineering.

Parametric blade representation

The blade profile parameters are the basis of the system.

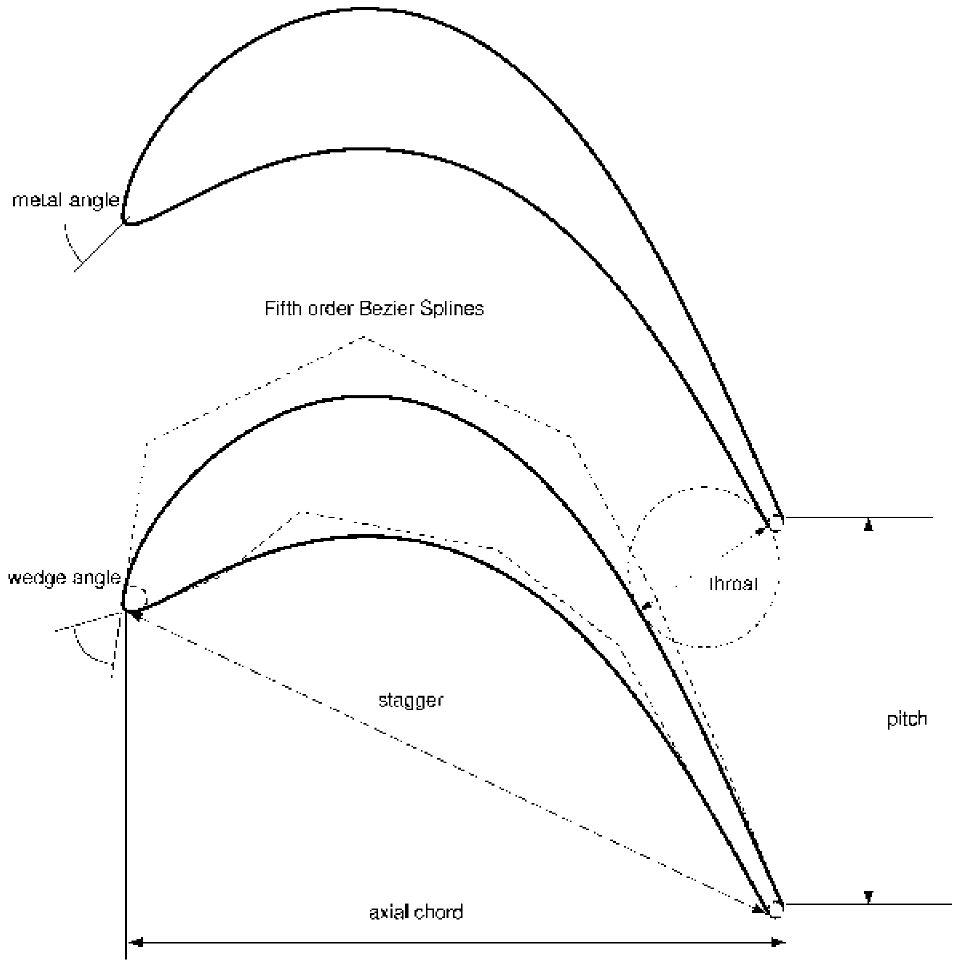


Abbildung 7 Blade parameter definition

The blade representation consists of two independent patches of higher order Bézier curves plus leading & trailing edge geometry. Special attention is to be paid to the treatment of the leading edge region. Currently both a circular leading edge and an elliptical leading edge definition are used. Slope continuity is always maintained at the joint points.

Rules-based design

In the first specification phase a so-called **AutoBlading** (**Auto**matic **blading**) project was set up to test the principal capabilities of the parametric approach and a rules based system for the design of a compressor or turbine blade.
The objective of the second project phase was to convert the trials system of phase I into an complete test system.
During the AutoBlading project phase II the scope was extended according to requirements from the compressor department and the availability of the new design program ***b2d***. On the other hand with the given resources it is not possible to create a complete design system.
Therefor the work focused on the implementation and testing of major parts of a design system to establish an effective alternative to the existing system.

The first idea of the AutoBlading project was to transform existing designs into the same unique parametric representation and detect similarity rules and correlation's between the aerodynamic performance and the throughflow axisymmetric conditions.
First of all, a tool had to be developed that derives these rules from the analysis of existing configurations. A simple SAS application has been developed to support this task.

Based on this tool, rules and blades for various existing and new compressors were created, e.g. the BR715 Booster, HP9 research compressor, Trent500 and Trent800 HP compressor.

Finally, the rules-generated AutoBlading blades were analysed and compared with its conventional design. In this sense, conventional design means design with the traditional blading geometry generators.

Derivation and editing of rules - software „auto_blader“

Within the project a rules generator was developed. The generation and modification of correlations between the throughflow- and profile parameters is implemented as an SAS tool. With this tool it is possible to calculate algebraic formulas for the x and y axis with the following set of parameters:

Throughflow-parameter		profile parameter	
AI	Air inlet angle	MUI	Inlet wedge angle
AO	Air outlet angle	MUO	Outlet wedge angle
MAI	Air inlet Mach number	BIA	Blade inlet angle
MAO	Air outlet Mach number	BOA	Blade outlet angle
REYNOLDS2	Outlet Reynolds number	RADT	Radius trailing edge
H2H1	Streamline contraction	RADL	Radius leading edge
SCX	Space chord ratio	STAG	Stagger
CL	Lift coefficient	CHORD	Chord length
PI	Pressure ratio	CURVISS	Inlet curvature suction side
XCHORD	x-Part of chord	CURVIPS	Inlet curvature pressure side
PHSEC	Percentage of height	CURVOSS	Outlet curvature suction side
NOB	Number of blades	CURVOPS	Outlet curvature pressure side
ZWEIFEL	Zweifel criterion	TANGISS	Inlet tangents suction side
RS	Rotor or stator	TANGIPS	Inlet tangents pressure side
		TANGOSS	Outlet tangents suction side
		TANGOPS	Outlet tangents pressure side
		STIFFISS	Inlet stiffness suction side
		STIFFIPS	Inlet stiffness pressure side
		STIFFOSS	Outlet stiffness suction side
		STIFFOPS	Outlet stiffness pressure side

The throughflow-parameters were extended for both compressor and turbine use (Zweifel criterion, lift coefficient etc.). The formulas for x and y are allowed to be mixed up by both parameter types. However, it has to be kept in mind that the rules must built up a linear system of equations which should be consecutively solvable.

In addition, x and y are stochastically analysed and plotted in a diagram for existing compressor data by SAS. For the rules, fit functions in polynomial form with grad 0 to 3 were used. With

SAS it is also possible to select area restriction in the plot and in the analysis so that exceptions of the rule can be extracted.

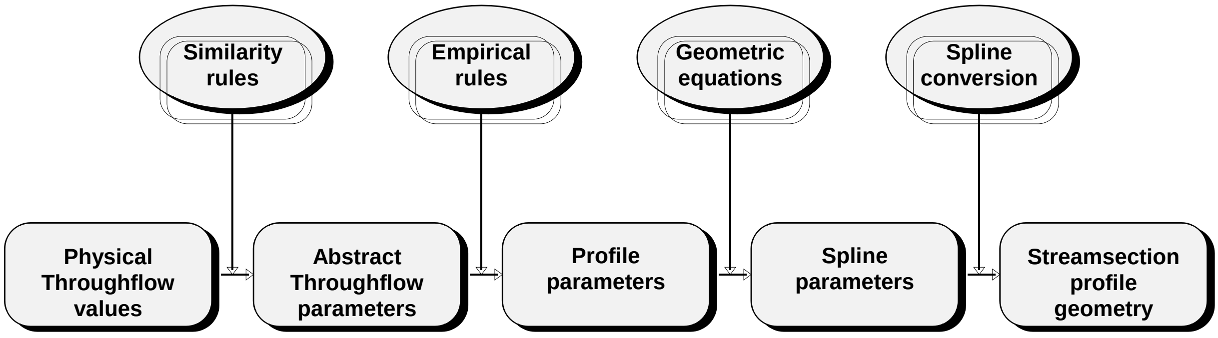


Abbildung 8 Rules-based AutoBlading process

Rules generation process

Two ways of rules creation are found:

- **Investigation of data of conventional designed compressors and turbines**

  The data of existing gas turbine components are reviewed. Three ways of making rules were found:
  - usage of physical dependencies and simulation of technical formulas
  - trial-and-error methods
  - automatic correlation of each single throughflow-parameter with each single profile parameter in order to find polynomial dependencies of degree 0 to 3

  In many cases, these rules fit well for the existing compressors and turbines. Only Method three turned out to be not flexible enough to get acceptable correlations.
  However, with an aerodynamically determined domain decomposition of the complete set of blade sections the correlations could be highly improved. Separate rules were generated for rotors and stators, transonic and subsonic compressor sections etc.

- **Adaptation of existing rules**

  Existing rules of conventional designed compressors were taken and adapted for the target compressor in view of the resulting blade. The rules adaptation is tested for some sections and transferred to the whole compressor. In many cases, these rules fit only for the objected compressor. However, this can help detect scattered design sections. This is helpful for the quality check within large teams of aerodynamic experts working on a single component.

Based on the SAS tool, different sets of rules and blades were analysed and generated:

1. **BR715 Booster**

   Based on the first BR715 booster design, rules were made and applied to the booster aerodynamic. The resulting blades showed an improved efficiency and performance compared with the conventional blades. The reason of this improvement is not quite clear. Most likely a smoothing of the section geometry parameters with respect to the throughflow data may have caused the effect. However, also the improved section curve smoothing can be reason for the better performance.

2. **HP9 research compressor**

Here, the rules of the PRIME HPC were applied to the planned aerodynamics of the HP9 high loaded research compressor. The resulting blades did not reach the desired performance due to the advanced loading. It was found, that the definition area of the rules was extended in Mach number and camber. The adaptation of existing rules showed reasonable results.

3. **Three spool engine HP compressor**

The blading of 2 different HP compressors of three spool aeroengines were analysed.

Highly loaded HPC
The highly loaded HPC had a new design style with an unconventional 3D design. The first simple approach of rules derivation for these blades failed, the data looks scattered. Thus, the fit function resulted in large Root-Mean-Squares and standard deviations. It was impossible to recreate the blades by using the existing rules and the desired aerodynamics.

Lower loaded case
Based on the existing rules BR715 HPC, BR715 Booster and three-spool-high load HPC, different bladings were created. The three-spool-high load HPC rules showed the best results, because of the aerodynamic similarity of both compressors, and because of the low loading of the compressor compared with the highly loaded case. Only incidence, deviation and curvature distribution on suction side had to be adjusted to come to a reasonable 2D blading. The adjustment was fulfilled manually with the **b2d** parametric section design program.

4. **High lift turbine**

BRR turbine blades consist of elliptically shaped leading edges. The quintic spline fit of elliptical leading edges combined with profile shapes is poor. Thus, a special leading edge parameter adjustment is necessary to improve the parametric fit for turbines and to find satisfactory rules. However, according to the test cases the rules-based profile generation is also feasible for turbines.

Parametric 3-D blade manipulation

To complete the idea of automatic creation and simple manipulation of a complete „parametric" compressor, a set of additional activities was required. First of all, a simple tool **b2d** for the generation and modification of a single parametric profile section was developed. This **b2d** tool was gradually extended during the project and is now in a form to control and modify all major aerodynamic parameters of a 2-D section.
The idea of using B-spline curves and surfaces for the generation of smooth blade geometry came up already 20 years ago. The problem with that is, that the terminology of B-splines has very little to do with the parameters the aerodynamic engineer uses for his design. The idea of **b2d** was to replace the B-spline parameters with aerodynamically meaningful parameters as far as possible.

However, some parameters are not transferable one-to-one into the B-spline description. Especially the standard procedures for the adjustment of profile thickness and suction side curvature distribution were requested. Both tasks have been solved with numerical procedures. These procedures were inserted as standard options into the AutoBlading system.

Furthermore a simple low-parametric representation of the 3-D stack for a complete blade consisting of a number of sections was requested. This approach has been implemented with a parametric stacking program **stack3d** (ref. /20/,/21/). **stack3d** gives aerodynamic designers a powerful, fast and flexible tool for creating specific 3-D blade properties.
A major disadvantage of most existing design systems is the principal inability to carry „lessons learned" automatically from one engine design project to the next. **AutoBlading** inherits the best assumptions to solve this problem. A parametric cloning option was developed to help carry experiences of previous designs to a new project.
Finally, the pilot implementation of **AutoBlading** did reach a degree of complexity and functionality, that a systematic analysis and improvement of the heterogeneous implementation was necessary. After that a user-friendly desktop-integration was developed and an concept for the integration of that into the BRR engineering environment was set up.

Linear & standard suction side curvature

The suction side curvature distribution is one of the major design items for compressor profile design.
Currently different philosophies are applied to get best aerodynamic profile properties.
To support the suction side curvature design work a set of standard curvature distribution options have been developed. These options create a linear or convex curvature distribution for the suction side profile geometry. Changes to the geometry are normally minimal due to the properties of the second derivative equivalent curvature.
Pressure side geometry as well as blade inlet and exit angles remain unchanged. Blade thickness may change slightly. It is recommended to apply the standard curvature options first and the correct the blade thickness. This will result in a profile with an optimal curvature + required thickness.
More details of the mathematical procedures for standard & linear curvature design are given in the next section.

Mathematics of Standard Curvature Distribution

A curvature distribution of a 2D curve is said to be standard if it is monotone and slightly convex (almost linear).

Denoting the two components of a curve x(t), y(t), with t being a parameter living in the unit interval [0,1], the curvature is defined:

(1) $$c(t) = \frac{\dot{x}(t) \cdot \ddot{y}(t) - \ddot{x}(t) \cdot \dot{y}(t)}{\sqrt{\dot{x}(t)^2 + \dot{y}(t)^2}^3}$$

The definition of a standard curvature may be described as:

(2) $$\ddot{c}(t) = w(t)$$

with a non-negative but small right-hand-side.

Since scaling and rotating does not change the curvature pattern, it is no loss of generality to consider only curves that start at the origin and end at (0,1). Now restricting to the curve which are closed to the x-axis one may replace the curve parameter t by the x- co-ordinate and thus considering only functions. With this approximation (1) simplifies to:

(3) $$c(x) = \frac{\ddot{y}(x)}{\sqrt{1+\dot{y}(x)^2}^3}$$

Now denoting:

(4) $$y_1(x) = y(x), \;\; y_2(x) = \dot{y}(x), \;\; y_3(x) = c(x), \;\; y_4(x) = \dot{c}(x)$$

(1), (2) may be rewritten as:

(5a) $$\dot{y}_1(x) = y_2(x)$$

(5b) $$\dot{y}_2(x) = y_3(x) \cdot \sqrt{1+y_2(x)^2}^3$$

(5c) $$\dot{y}_3(x) = y_4(x)$$

(5d) $$\dot{y}_4(x) = w(x)$$

w(x) denoting a non-negative small prescribed weight function. In order to obtain a unique solution 4 initial or boundary values must be provided. It is already assumed that

(6a) $$y_1(0) = 0$$

(6b) $$y_1(1) = 0$$

In blading users usually want to control the tangent of the shape. Thus the remaining two boundary conditions will be:

(6c) $$\dot{y}_1(0) = \tan(\varphi_0)$$

(6d) $$\dot{y}_1(1) = \tan(\varphi_1)$$

with given angles φ_0 and φ_1.

A solution of (5), (6) can be calculated by utilising a standard software package. In ***b2d*** the IMSL routine BVPFD is used.

Experience shows that the choice $w(x) = (\varphi_0 - \varphi_1) \cdot x/50$ or $w(x) = (\varphi_1 - \varphi_0) \cdot (1-x)/50$ gives good results.

The output of a boundary value problem solver BVPFD is a number pointwise given curve. Thus it remains to find curve parameters such that the resulting curve fits best to the points. This is done with the fit algorithm that is already introduced in the system.

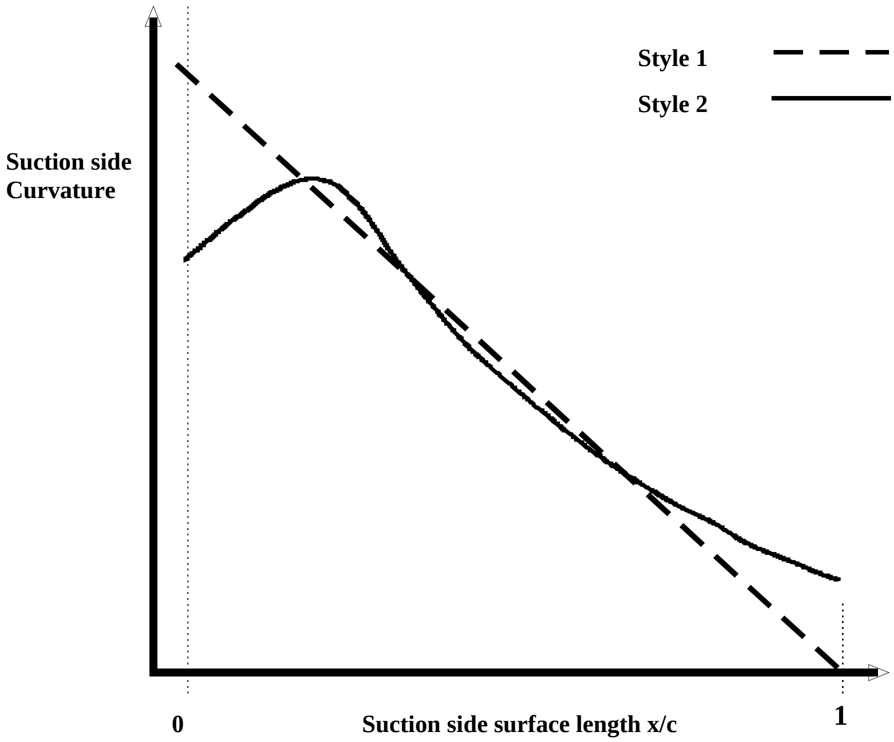
Suction side curvature distribution, form factor H and loss loop

For the geometry design of compressor blades companies normally use a set of standards and rules describing the principal shape properties of an acceptable blade geometry. Amongst those is a recommendation for the suction side curvature distribution.

This recommendations frequently used basically say that the suction side curvature should have a decreasing distribution from the leading edge to a a minimum at the trailing edge of the blade.

The analysis of various public available profiles from research projects reveals different design strategies for this particular feature. Some profiles have obviously been designed with a strictly linear suction side curvature distribution ending at zero curvature at the trailing edge.

The principal setup of the 2 most common styles is sketched in figure 1:



The effects of these different approaches have been compared in a little design study. The ***AutoBlading*** geometry tool **b2d** has been used in a quasi-inverse design mode starting from two existing profiles. The objective was to implement the style 1-like linear decreasing curvature feature with a minimum of geometry change.

Test-Profiles		
Case 1:	original design	BR710 HPC Rotor 5 mid section
	redesign	BR710 HPC Rotor 5 mid section
Case 2:	original design	HPC Rotor 1 near hub section
	redesign	HPC Rotor 1 near hub section

Figure 1 shows the original and the redesigned profiles with their respective curvature distributions.

Results and discussion

The resulting loss loop for case 1 is shown in figure 2 in the appendix. This plot clearly shows

- lower losses in the design area
- an extended off-design range

The blade tolerates a broader incidence interval. Moreover, looking at the shape factor H for the design point calculation, we get the following result (case 2, figure 3 - 5 in the appendix):

original	linear increasing shape factor up to 2.7 (at the trailing edge)
redesign	convex increasing shape factor up to 2.3

From these results it can be estimated that the boundary layer of the redesigned blades is less loaded and will sustain off-design situations more stable.

Another (presumably partly numerical) effect is that the linear curvature profiles have a better convergence within the used blade-to-blade solver MISES thus reducing the computation times. This effect may be partly due to the influence of surface curvature terms in the boundary layer calculations.

The results presented above are clearly only indications of possible advantages of the ***linear curvature*** design rule. More investigations are at hand to validate these results and find possible conclusions for future design work.

The results of these investigations may have an profound impact on the ***AutoBlading*** integration project. A rule like the one from style 1 type blades will reduce the number of free geometric parameters. It is possible to implement this rule in the ***AutoBlading*** project which leads to a remarkably simplified design procedure.

Thickness correction

With the approach of separately defining suction and pressure side profiles blade thickness is not a direct design parameter. To define blade thickness and thickness distribution (i.e. position of maximum thickness) a separate method had to be developed.
The methods asks the user for the value of the section thickness. The required thickness will then be maintained by a minimum change of the pressure side geometry. The result will be a smooth airfoil with the required thickness. Blade inlet and exit angles and suction side geometry remain unchanged throughout the procedure. Details of the thickness correction procedure are outlined in appendix 6.

In the setup of the AutoBlading rules neither the blade thickness nor the position of maximum blade thickness appear as parameters. Both thickness and position of maximum thickness are fundamental values for the design, particularly of high pressure rotors. For each of them usually design constraints and intervals are given to meet the stress and vibration criteria.
In order to insert these parameters we have different possibilities. Within the parametric blading design system we have selected one out of these different alternatives, which appeared to cause the most uncritical changes to the blade geometry. So the objective was to

meet the required blade thickness and position of maximum thickness with minimal variation of blade geometry and rules.

Distance function

A possible distance function is given by the following sum of squares of weighted differences

$$diff=100*\Delta incidence^2+100*\Delta deviation^2+10*\Delta wedge\_inlet^2+10*\Delta wedge\_outlet^2+2*\Delta curvature\_inlet^2+...$$

For that we have to answer 2 questions:

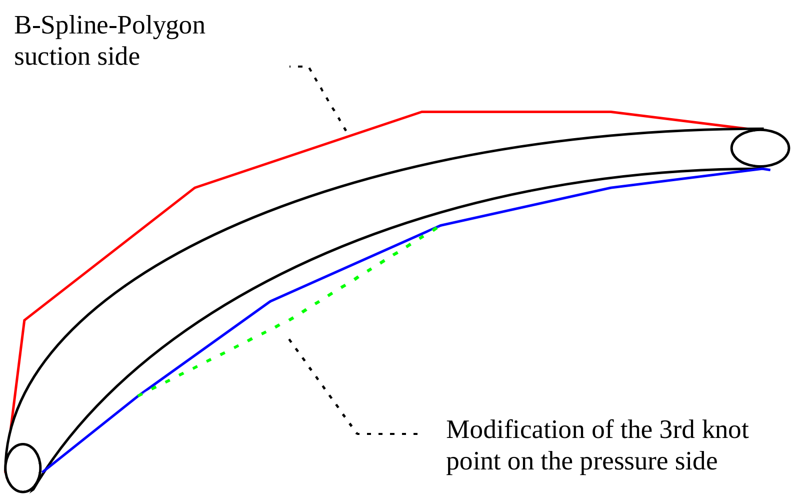
1. Which parameter can be free in order to set thickness?
2. How do we have to weight these degrees of freedom?

Variant 1:

On the pressure side of the profile knot point 3 of the B-spline polygon (from the leading edge) is set free both axially and circumferentially. These extra 2 degrees of freedom are sufficient in most cases, to correct between 25%-50% maximum thickness position and correct maximum thickness.

Variant 2:

Release the leading edge wedge angle and knot point 3 of the B-spline-Polygon (counting from the leading edge) in both directions. With these extra 3 degrees of freedom most likely all practical design changes for thickness and thickness position can be carried out.



Picture 9 Variant 1: Knot point 3 on the pressure side is free design parameter

Both alternatives have the advantage, that they do not change the suction side profile, i.e. they do not affect the diffuser performance of the cascade. More other variants are possible.

Variant 2 has been implemented with a little IMSL-Routine ***uminf*** (unconstrained optimisation of a multivariate function with finite difference gradient). Based on that other variants can be implemented easily.

Defining target functions - general approach

To proceed further, a set of general questions has to be answered:

1. Which additional design data has to be considered in the rules for the AutoBlading? This could be loading distribution (front/rear loading, radial variation of incidence), choke margin, stall margin etc.
2. Which geometric parameters should be free for adjusting these additional design targets?
3. What is the weighting for these target parameters?

To answer this questions, we have to take into account the different process approach of the parametric design compared to the traditional design style. If the designers previously directly manipulated geometry in order to achieve the desired aerodynamics, we are now in the position to manipulate the target function and its components and weights. The profiles are then generated automatically according to the target specifications. This is usually named inverse design. The variability and flexibility of the target function and the quality of the change methods is important for the work of the engineer. Therefor the above questions have to be answered carefully to get the right answers for an individual design task.

Parametric 3-D stacking

Once the 2-D streamsurface profiles are defined, they have to be stacked to give the final 3-D blade shape.

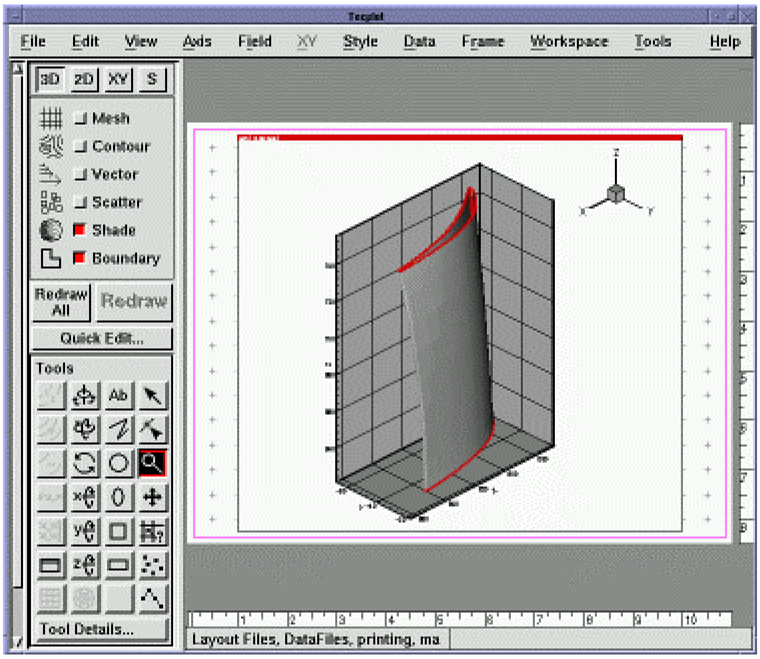


Abbildung 10 TecPlot display of stacked blade

This is a tedious and complex task for real 3-D shaped blades. Therefor a simple procedure has been developed to simplify this and make it repeatable. This procedure is based on a parametrisation of the major stacking options. The specification of the stacking parameters is described in reference 20.

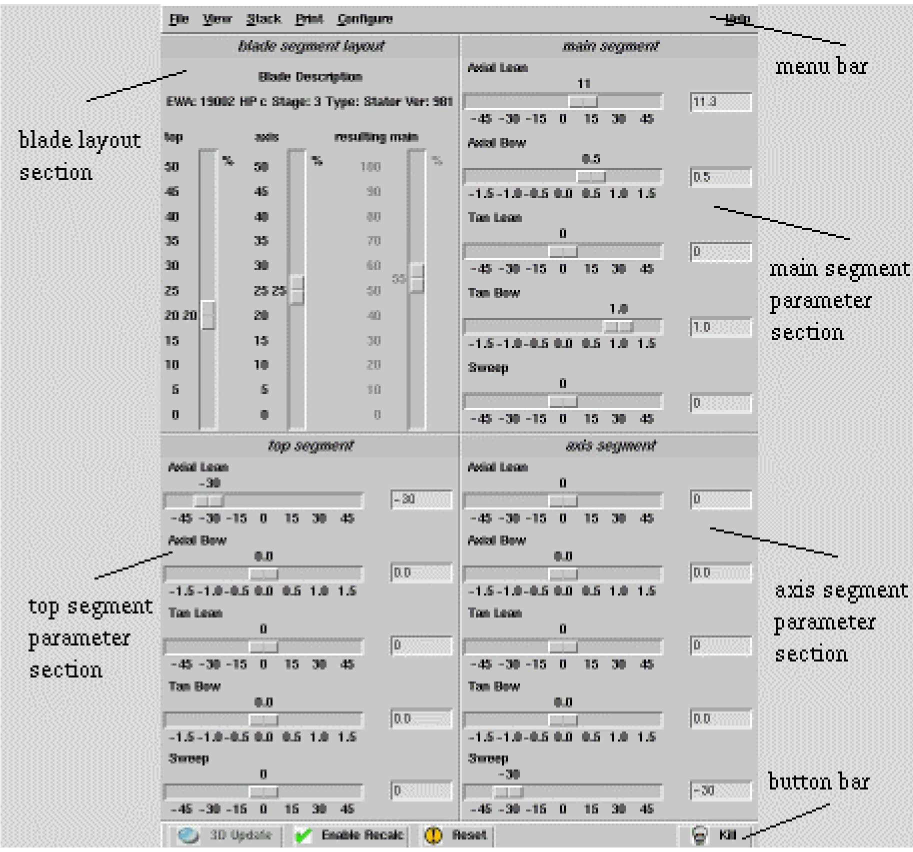


Abbildung 11 GUI for the parametric 3-D stacking program

The **parametric 3-D stacking** was implemented in a program **stack3d**. A detailed description of **stack3d** including user guide and implementation details in contained in Ref. 21.

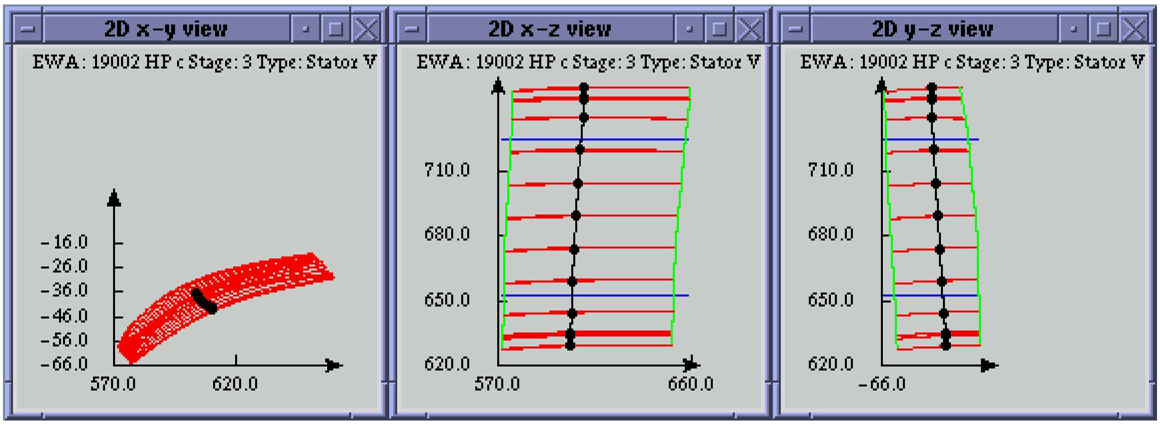


Abbildung 12 Standard views for parametric stacking

Radial blade smoothing and interpolation

Usually the complete blade is defined only on 3 to 7 intermediate sections along the total height of the blade. To convert the blade into the CAD system 21 sections are necessary to give the required accuracy. To get the 21 sections out of 3, 5 or 7 originally defined sections an interpolation process is carried out. With the parametric section the best approach is to interpolate these sections in the parameter space. This will result in smooth airfoils.
The interpolation result can be checked in the parameter space. If further radial smoothing of the blade is necessary, this can be done by smoothing the parameter distribution along the blade height.
A **radial blade smoothing and interpolation** tool ***rit*** has been developed to carry out these tasks. This tool is fully integrated into the design system. It can also be used to optimally smooth existing profiles very easy. ***rit*** has a direct interface to the parametric CAD systems and can directly create a CADDS part.

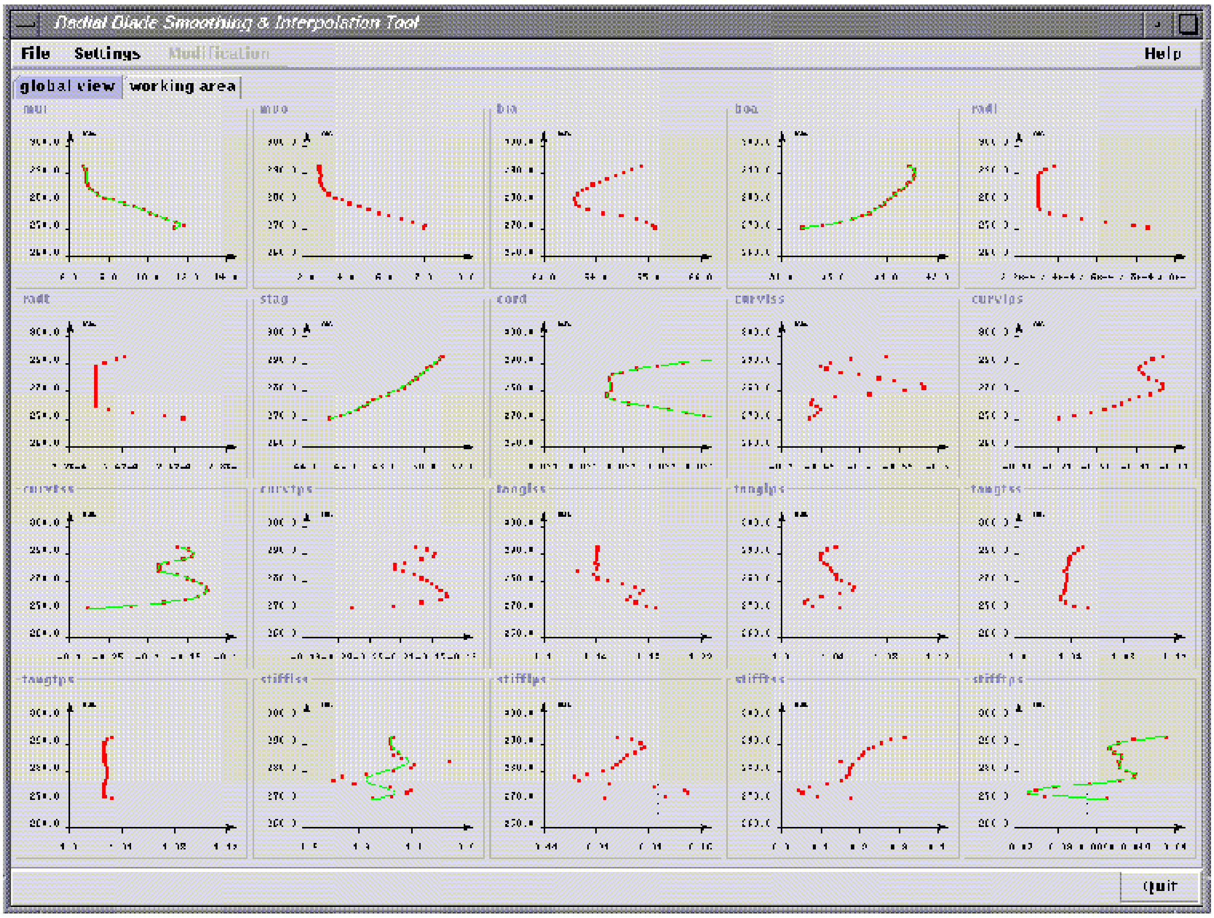


Abbildung 13 Radial Blade smooting & interpolation tool

Ref. 22 contains a description of the ***rit*** tool.

Profile optimisation

A blade section that is result of the **AutoBlading** algorithm is expected to be approximately 90%-95% as good as an optimum solution. The quality of these section is considered to be sufficient to work with in a 3D design strategy. With a set of autobladed sections one may do further 3D design by applying sophisticated stacking methods e.g. sweeping, bowing, and leaning of blade shapes and analysing these geometries with a 3D analysis tool.

Another application which may be even more important is optimisation. An autobladed section is an excellent starting point for an automated optimisation algorithm. The current discussion both internally and with external contacts shows that the major activities to take place are as follows:-

- Adjustment of the parametrisation to the requirements of usage in automated optimisation environment
- Development of an objective function that is capable to support the engineer's design intend
- Selection of an optimising algorithm applicable to the problem of blade section design

The authors of this report are convinced that there will be a major benefit for our company in terms of lead time and development costs to have an optimisation tool in place. It is known that in

other companies (e.g. ABB, SIEMENS) there are existing running projects on blade section optimisation. Hence it was recommended to start according activities.
As a rapid prototyping result a section geometry optimiser **BladeOpt** was developed. This tool optimises blade sections based on MISES calculations. The user can interactively define target functions and constraints. **BladeOpt** will the create an optimum blade shape within a couple of minutes on an average workstation.

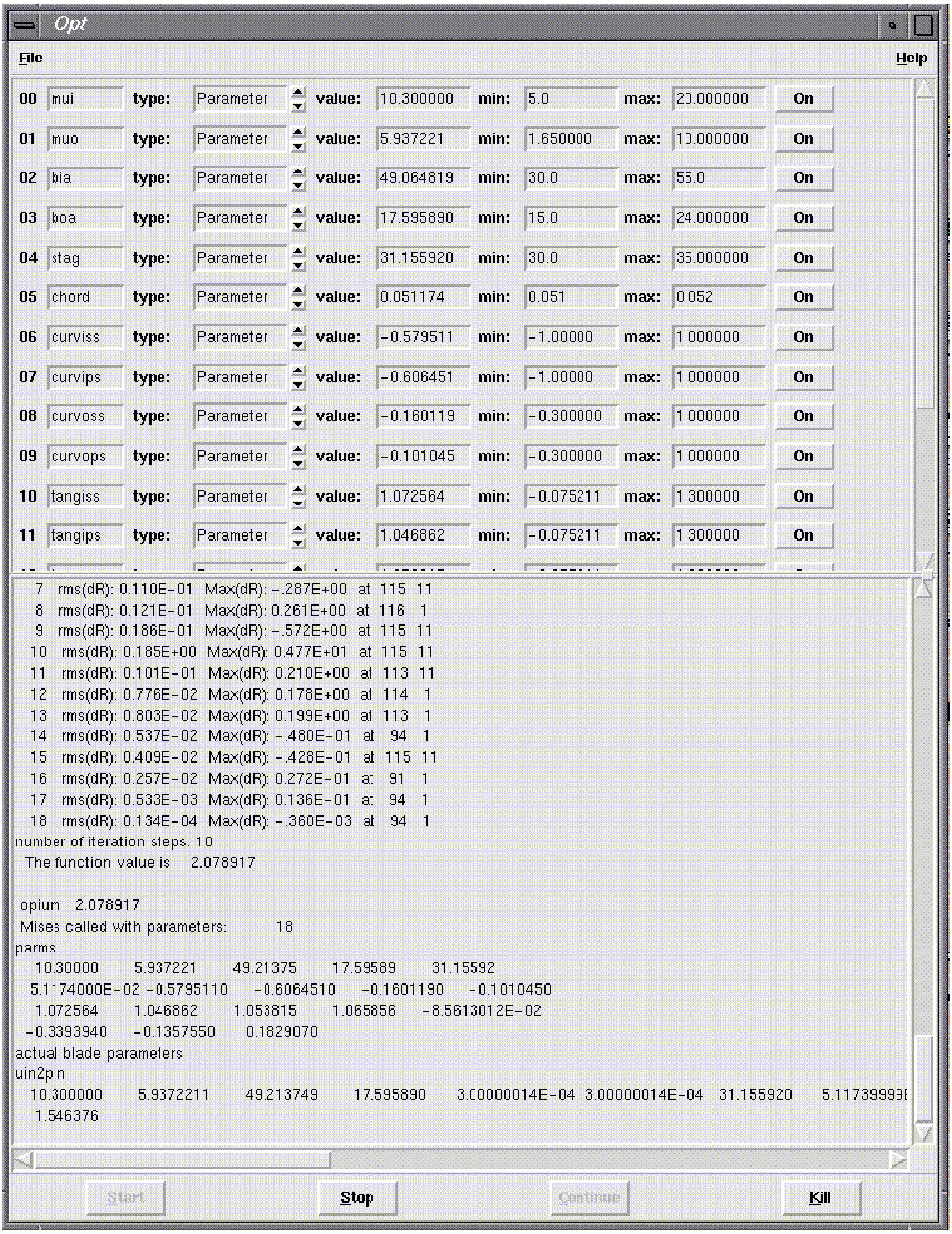


Abbildung 14 BladeOpt profile optimisation tool - parameter and constraint management window

The optimisation routine in **BladeOpt** will find geometrically similar profiles. The user can interactively specify which blade properties should remain unchanged and which properties can be optimised.

- AutoBlading results in smooth parameter set
- Optimisation in sub-space (of the total parameter space, eg. normal to blade surface)
  8 => 4 free parameters
  will result in smooth parameter set

Target function components

- thickness f1
- outlet slope f2
- pressure ratio f3
- loss (visous, wave) f4(total) f5(visc), f6(wave)
- spike ss-ps f7,f8
- choke margin
- shape factor H, Hbar
- machnumber distribution
- loading characteristics

A detailed description of **BladeOpt** is given in Ref. 23.

Design process

Fundamentally, it is possible to create blades supported by the **parametric blade design system**. This could be demonstrated with the **AutoBlading** testcases BR715 Booster and the three-spool engine HPC.
However, the blading algorithm is a complex and sequential task. The original intention of fully automatic creation of a final blade design by means of rules applied to aerodynamic throughflow conditions turned out to be not a feasible objective. However, the **AutoBlading** system generates a reasonable design within seconds based on rules and experience knowledge. Keeping that in mind a new blading procedure was defined. This new process starts with an initial preliminary design either from **AutoBlading** or from an existing cloning blade. In the next steps the applied rules have to be optimised in view of the resulting blades. Fine tuning is to take place in the parametric profile modification program ***b2d*** where each section must be modified manually.

The aerodynamic blade design process basically consists of the following steps:

- setting of incidence and deviation supported by 2D CFD calculation with a 2-D blade-to-blade solver
- setting of blade thickness
- setting of suction side curvature distribution monotone and smooth
- fixing of blades in aerodynamic block
- increase choke margin up to the required percentage by moving the stagger
- create all required interpolated sections
- radial smoothing (if necessary)
- parametric stacking

- creation of parametric CAD blade with class A high quality surfaces

The parametric CAD model can be represented in a standard CAD solids format like ACIS or Parasolids. This particularly improves the interface to platform/foot design, stress calculation etc.

The above described process is sufficient for the design of „2-D“ blades, not particularly designed for 3-D effects such as passage vortex and tip clearence. However, it gives a fully parametrized description of the 3-D blade shape and hence allows optimisation towards all of these 3-D aerodynamic effects. The parametric blade design systems forms a bais for the design process. How it is used for different design tasks depends on the design philosophy of the individual cases.

Software quality and integration

A production tool to support the blade design process has to fulfil some fundamental software conditions. In this sense, the parametric design system has to support all necessary workflow and process functionality for the user.:

- Workflow information:
  - Where am I now?
  - What am I doing here?
  - Which section do I edit?
  - Which sections are displayed?
- user interface features:
  - Use of Scroll-Bars
  - Manual input of values
  - Error-Management at array limits
  - Rounding
- error checking for input values
- read/write access control and security for concurrent simultaneous engineering
- life cycle and database information: Which sections are in work/release?
  Which projects are running? How many blades are released already?

Testing and introduction as project standard

This new parametric blade design system is based on a fundamentally different approach than existing geometry systems like the one’s used currently at RR. There are technical as well as process-oriented advantages with the new system leading to a better design within less amount of engineering time.

But - as always - using the system and exploit the advantages of the new technology requires user training, learning and acceptance of the differences. This is the critical success factor for the return of the investment into this new technology. A company will only get the real benefit out of it if they decide to go for it, use it and incorporate the necessary changes in the interfacing processes.

Aerodynamic Standard profile properties with the *Parametric Blading system*

To meet the requirements of a standardised profile geometry generation process standard profile properties have been introduced.
The user now has the choice of selecting

- **standard curvature distributions**
  This option offers two different options for standard suction side curvature. Both options will create a convex decreasing curvature on the suction side.
  Fixed parameters: all angles
  stagger, chord
  radius leading + trailing edge
  pressure surface
  free parameters tangent length, curvature + stiffness suction side leading + trailing edge

- **thickness correction**
  This option lets the user enter a desired profile thickness. This thickness is obtained by changing the leading edge portion of the pressure side profile
  fixed parameters all angles
  stagger, chord
  radius leading + trailing edge
  suction surface
  tangent length, curvature + stiffness pressure side trailing edge
  free parameters tangent length, curvature + stiffness pressure side leading edge

With these new standard profile options the new 2-D profile design process can be sketched as follows:

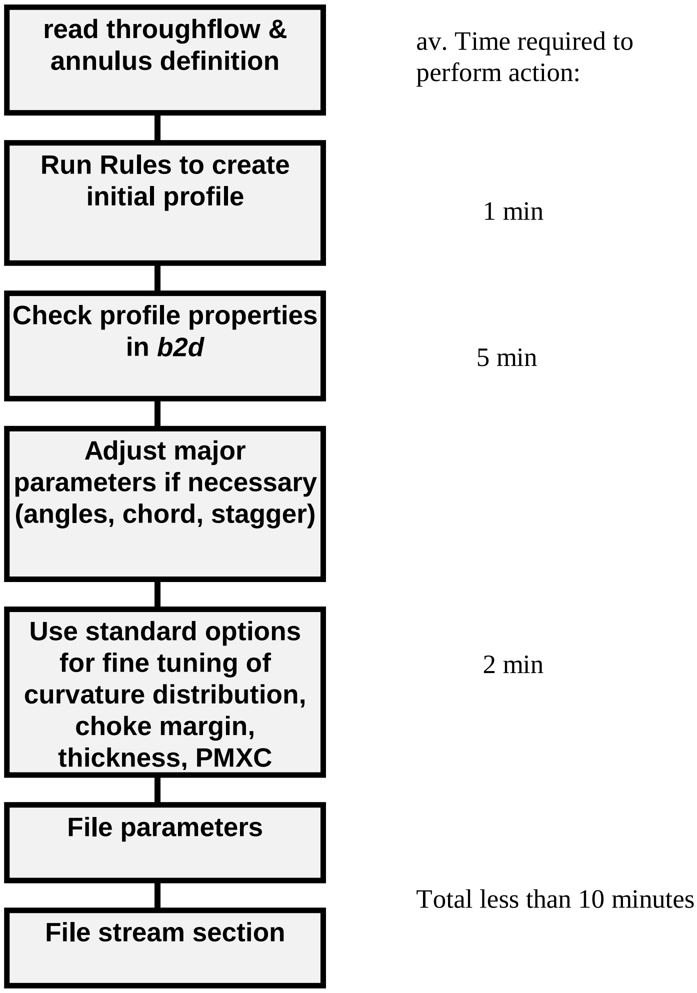


Abbildung 15 Profile design process

Throughout this process the aerodynamic engineer only modifies „meaningful“ aerodynamic-related parameters. The new standard options free the engineer from using the complex B-spline parameters **tangent, curvature** and **acceleration** with limited transparency for aerodynamic effects.

This approach is a combination of a fully CAD-compliant spline-profile representation and a simple standardised user interface to speed up the design process.

The **parametric blade design system** enables the user to design a 100%-Blade section geometry as a smooth spline parameter profile with the required aerodynamic properties for a given set of inlet- and exit throughflow conditions and a preferred suction side curvature distribution within less than 10 minutes.

Curve and profile representation types

Within the **parametric blade design system** different representations for the geometry are used for the different tasks. The conversion from one format to another is carried out with a set of programs and subroutines. The figure below outlines the main interrelationships and transfer routines.

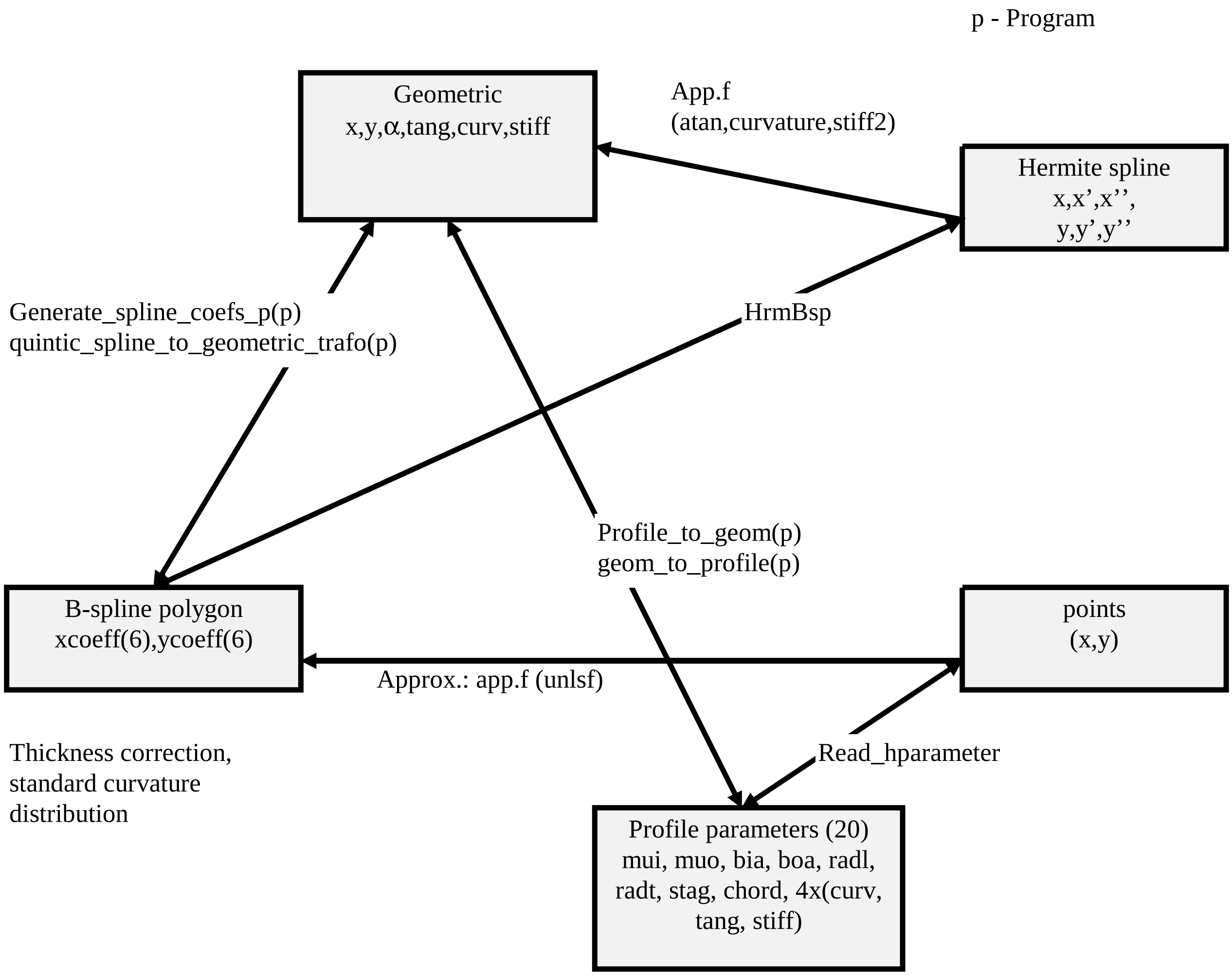


Abbildung 16 Profile representation types and interfaces

Cloning

A frequently repeated task in design projects is the adoption of the blade geometry to a slight change in the throughflow aerodynamics, e.g. to meet changed loading or thrust requirements. This process is called cloning.
It is estimated, that 80% of the design work is in fact incremental change of existing already designed parts.

One objective of the attempts to improve efficiency of engineering work for this tedious and long-lasting task is to reduce manual work and (at least partially) support it with automated features. This chapter proposes a way to get there by means of the parametric blade description.

Problem description

The workflow in the rules-based aerodynamic design is a sequence of rules applications and manual adjustments:

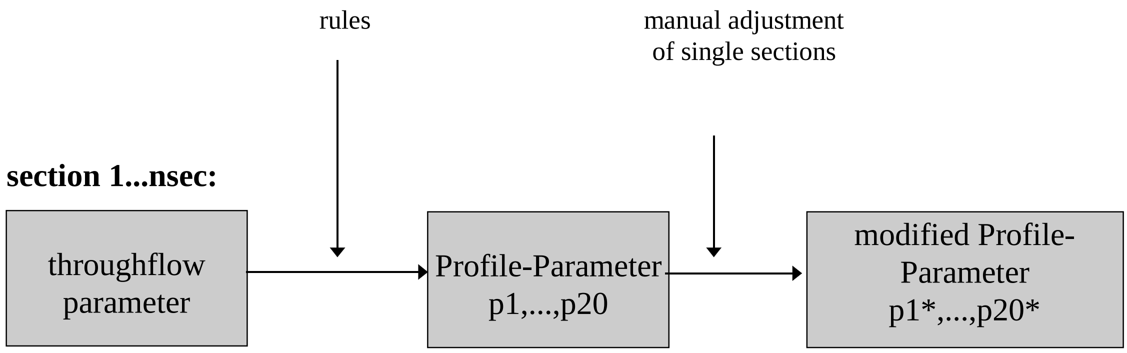


Abbildung 17 Design workflow

If during the design phase a new slightly changed throughflow data set appears, all manual adjustments to the individual sections have to be repeated. This is not feasible.

To solve the problem, the use of an offset-matrix was introduced. All individual changes beyond the automatically created blade sections are stored in an offset-matrix. These offset values represent the distance of each individual blade parameter from the rules-based automatic value. This is applied to all sections and all blades of a given design.

Since we can assume that the rules already create a reasonable geometry, offset values will usually be small and the disturbances represented by the offset matrix can be expected to behave linearly.

In case of non-linear effects or intentionally tweaked designs it is very difficult to trace and find correlations. For this cases a 2-stage process is proposed: First, the best statistical correlation should be derived and applied to the design task. As a second step, the perturbations from the correlation formula are added to the rules-based design in form of an offset-matrix. This 2-stage process ensures that the advantage of a rules-based process is kept and the necessary flexibility of designing individual features for certain sections is prevented.
The basic idea of parametric cloning is to carry design intent information from one blading project to the next by means of an offset-matrix.

Definition of the offset matrix:

The offset matrix is defined by

section i=1,...,nsec, parameter j=1,..,20: $\quad$ offset(i,j):=p(i,j)-p*(i,j),

where p(i,j) denotes the automatically created AutoBlading parameter j for section i and p*(i,j) denotes the manually adjusted parameter value for the same section for a reference design.

With that matrix in hand, we get a new design process.

In case of a new throughflow coming up, the following process is required:

New throughflow:

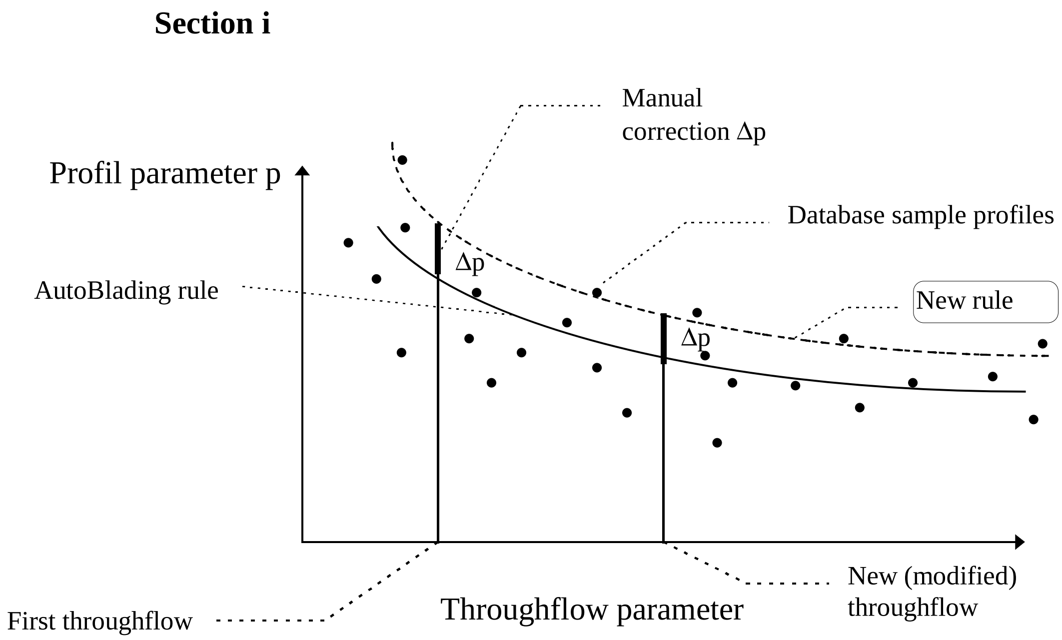


Abbildung 18 Offset matrix and design

1. application of rules to the new throughflow
2. increment the AutoBlading section parameters with the offset matrix
3. further manual adjustment of sections may lead to a new updated offset matrix

In case of a new rule, the user has to

1. take all offset information an throughflow data
2. create new correlations
3. create new offset-dataset (out of reference throughflow + previous offset dataset

This process guaranties an optimal fit of the blading to new throughflow data. Moreover, the information from the manual modifications is kept and can even be enhanced. With that technology in hand a step-by-step improvement of the design based on varying throughflow data is possible with minimal effort. With the traditional process every change in the throughflow design data had to be manually upgraded to the new boundary conditions.

Implementation & layout

The implementation of the offset matrix feature in a graphical user-interface is a straight forward rapid prototyping activity. New software-engineering technologies are used to achieve a user friendly and standardised stable software solution.
The principal setup of the graphical user interface in described in the figure below.

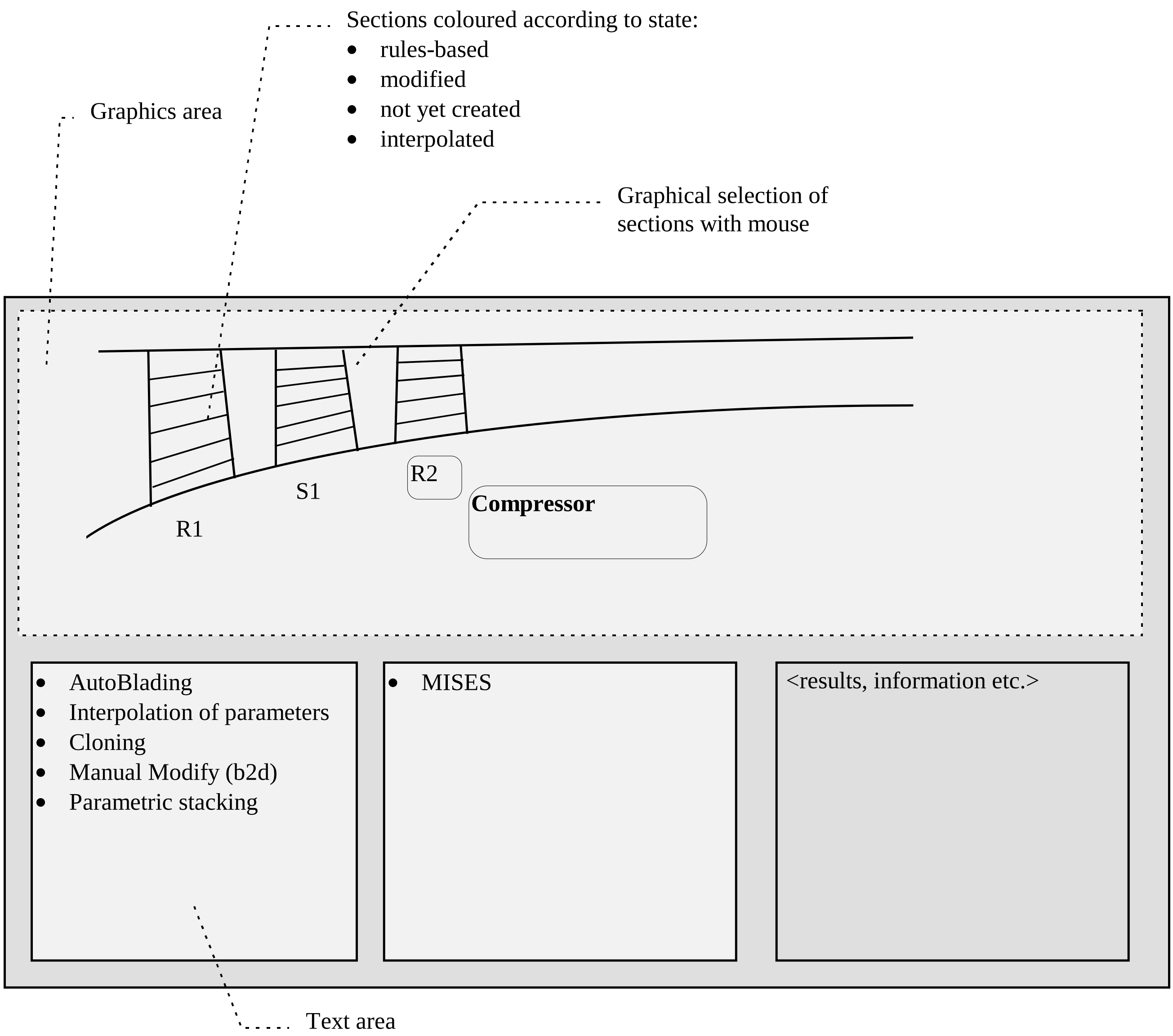


Abbildung 19 Integrated system blading - layout of user interface

Concept for the application of AutoBlading for design work

The AutoBlading system & technology has a high potential for the improvement of the design process. In order to have the full benefit out of this the system has to be integrated into the complex design environment.
This also requires changes in the affected working practices. The users will experience a learning curve till the point, where the parametric approach is fully integrated.

For in use of the system we have different alternatives depending on the focus of the project. This may be

- automation of procedures
- variability
- application to different types of engine components

- individual adjustments

Automation

The parametric rules based design approach is clearly not flexible enough to cover all possible compressors or turbines. I.e. for a new design project the rules need to be adapted. They are not so general to cover the whole design space. We will have individual rules for high speed compressors, low speed compressors etc.
Once the rules have been adapted to the individual case, the fine tuning is a relatively small task. That means that the main advantage of the system is in the speed-up of the iteration process in the design.

Cloning

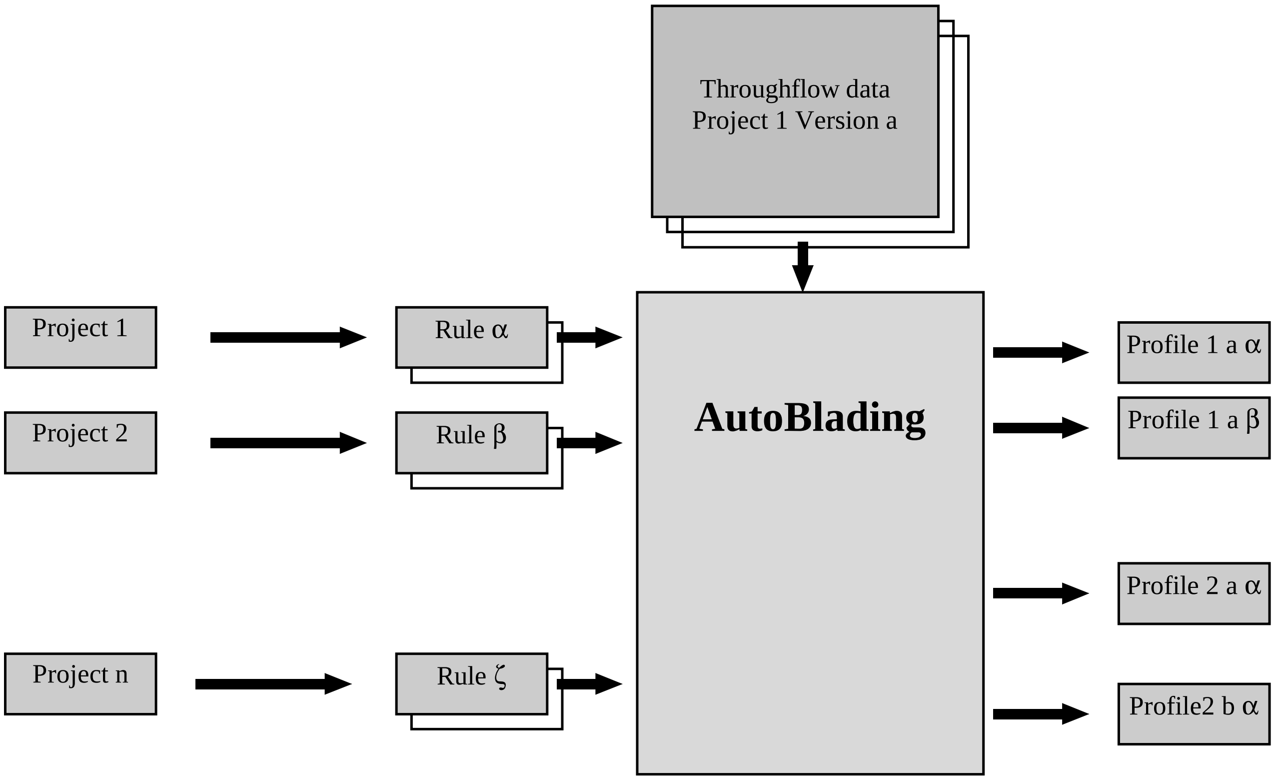
The main advantage of cloning is that we re-use knowledge of previous experience. We apply cloning rules from an aerodynamically similar previous blade which once has been optimised for a particular task to get a new blading configuration for new aerodynamic conditions. Thus we have a kind of „expert“ system with a knowledge base in form of parametrised data and correlations.
This advantage is only partially valid for the **AutoBlading** system itself, because a single rule is originally based on statistical interference, where all previous blades are equally weighted. Thus the individual previous blades are not weighted with respect to a „distance“ for the new design task. On one hand this keeps a required generality of the rules, since they are not designed for a singe parent blade set. On the other hand this causes difficulties to set correlations for some parameters with high variance.
To combine the advantages of both aspects a so-called **AutoCloning** has been adapted:

1. A Clone-Parent (Clone-profile+Clone-throughflow) is parametrised
2. for the Clone-parent AutoBlading parameters are detected out of Clone-throughflow
3. AutoBlading parameter are generated from the new throughflow
4. the new blade is new determined as a combination of:
   Blade inlet+outlet angle, chord from AutoBlading
   all other Parameters from the Clone-parent

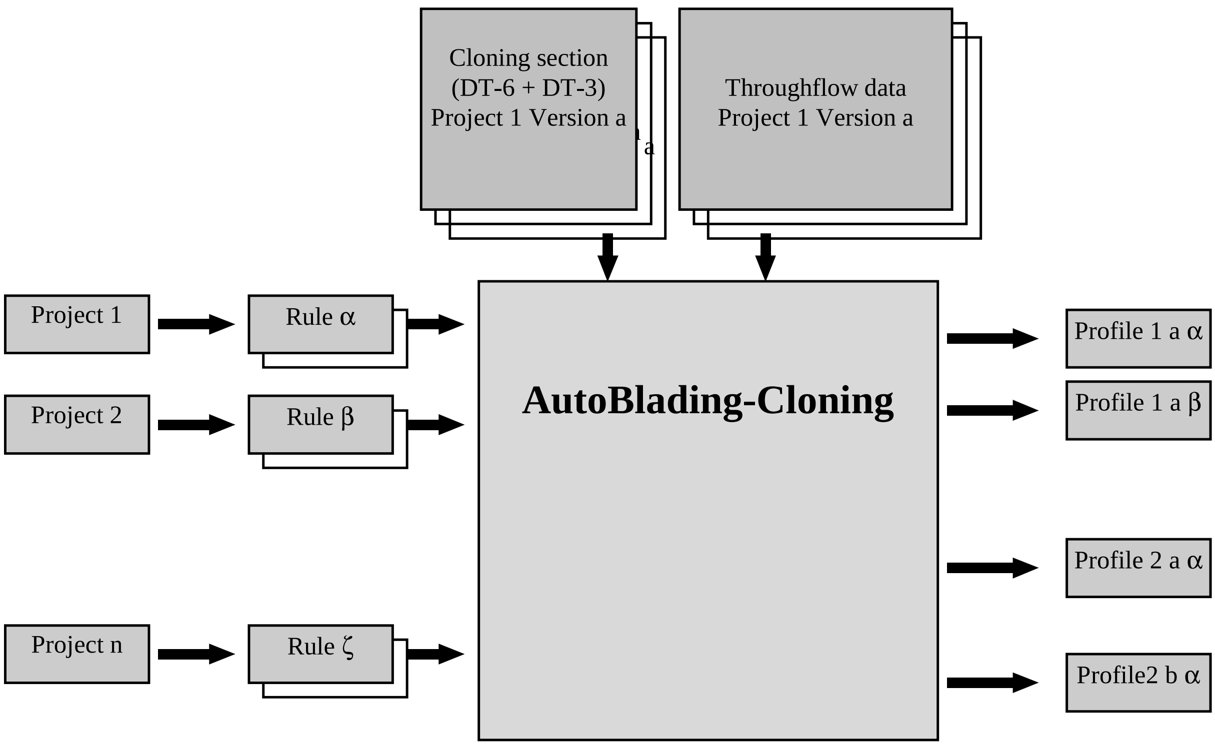
Example: Determination of Incidence

1. Clone BIA=55°, Air inlet=40°, Rule-BIA=52°
2. Rule for throughflow new: BIA=65°, throughflow-Air inlet = 45°
3. new Blade inlet = 45° + (55°-40°) 0 60°

With that we have the following procedure:



Picture 20 Design process with AutoBlading



Picture 21 Design process with AutoBlading+Cloning

From the process point of view, the cloning states a new requirement. Additional to the rules and the throughflow data, for each individual section a clone-parent (blade section and throughflow) are necessary as input data.

This work can simplified by providing a set of „optimal“ blades and let the AutoCloning process search for the nearest neighbour by means of a given distance function.

Application to Fan, Booster, HPC, HPT, LPT

The requirements for the different components are fundamentally different. The fan blade has to be designed individually in each section with large 3-D effects and major radial blade profile changes. For a typical booster and HP compressor the large number of blades is the major problem. They should all be designed according to similar rules and with the same blading philosophy. Turbines require a different parameter set, especially for low-pressure turbines the cloning in combination with an inverse design strategy seems to be the best choice.
The system supports an easy way of defining a large group of profiles with similarities for a complete component, to find design correlations and to correct them manually afterwards. This manual work is reduced to a very low effort. Usually only a small number of profiles has to be adjusted manually and these adjustments are restricted to a low number of parameters. Most of the standard actions can be carried out automatically, such as incidence and deviation setting, adjustment to aeroblock, setting of thickness and position of maximum thickness and standard linear suction side curvature distribution.

Blade design system integration

To get the real benefit out of the parametrics in blade design, the integration into the existing design procedures and systems has to be implemented.
Traditionally, there are 2 different ways to do that, and we call them here the *aerodynamic-centric* and the *CAD centric* integration.
The main differences of the two alternatives are outlined in the following table.

Aerodynamic centric versus CAD-centric

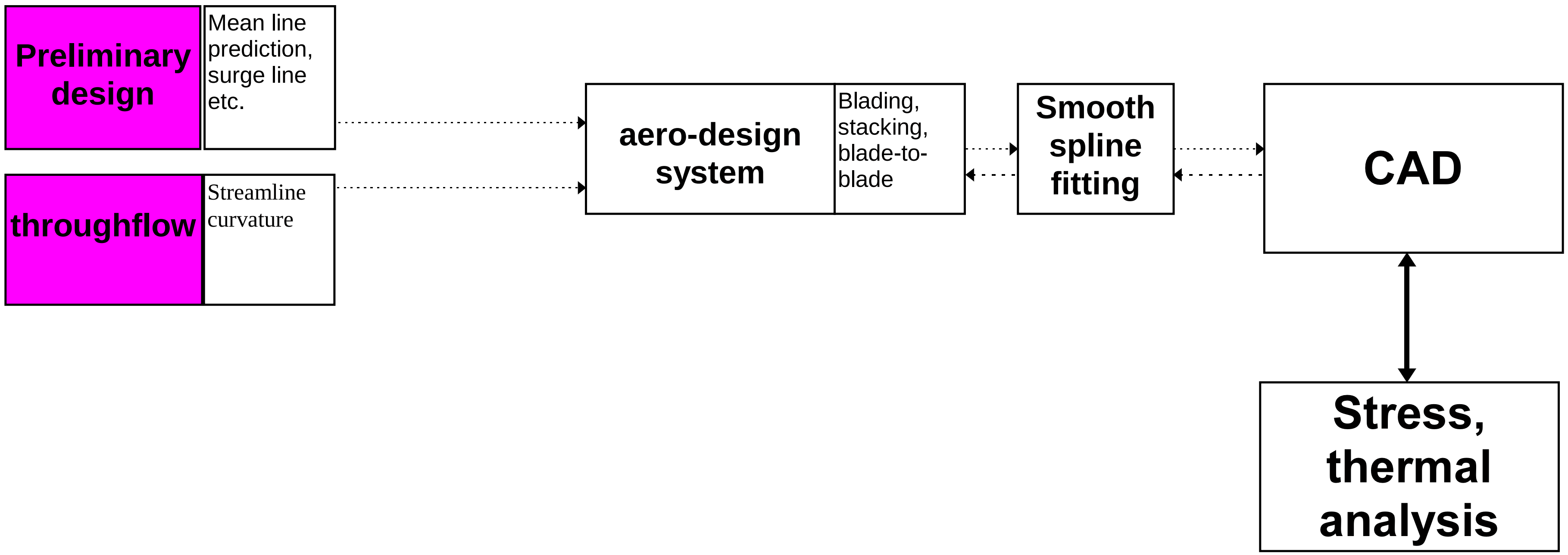
Aerodynamic centric	CAD-centric
• Aerodynamics defines blade shape with internal geometry definition • blade geometry is then transferred to CADDS (with some approximations) • advantage: very short iteration loops for Aerodynamic design • disadvantage: design loops with stress, CADDS very time consuming, multiple geometry data approximation leads to geometry errors	• Blades defined as CAD-surfaces right from the beginning • Aerodynamics creates intersections with stream surfaces for their purposes • advantage: better integration into CAD (virtually no interface required, no data translators etc.) • CAD license required to do aerodynamic design
solution: - identical parametric Blade geometry representation for Aerodynamics and CAD - standard Hermite splines of degree 5 - bi-directional data exchange between Aerodynamics, stress, design, CFD etc. **parametric integrated blade design system**	

What can be saved with the new process? What improvements do I have?

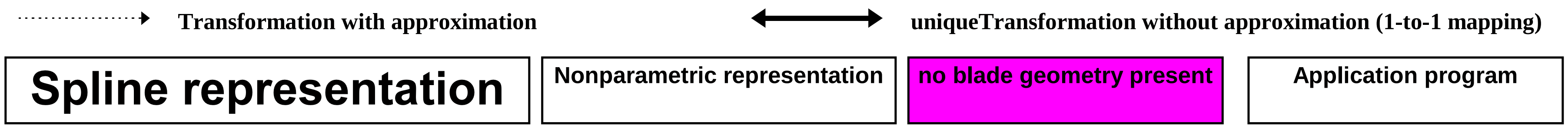
- design time -
  cycle time reductions from 6 weeks (per HPC) down to 5 days
- repeatability of design work
  due to parametric representation
- improved quality and uniformity of profiles
- common geometry representation throughout the whole design process

Integrated Blade design system

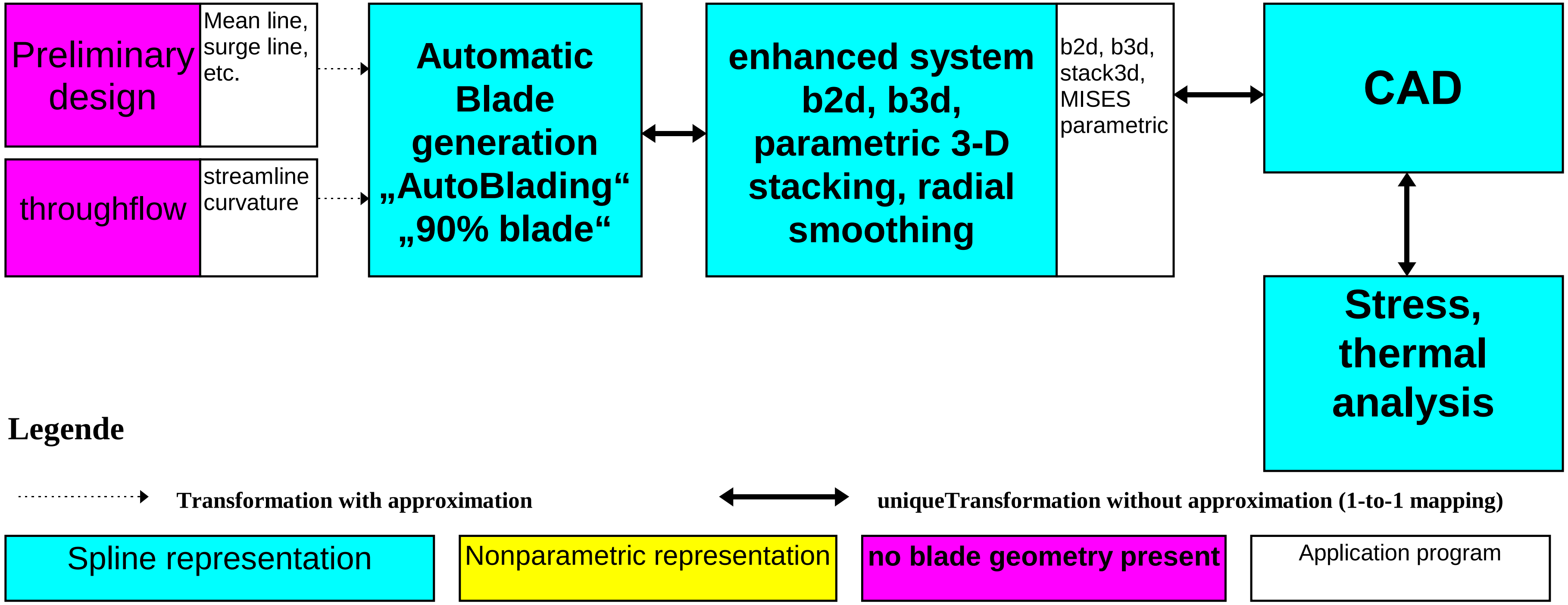
Traditional process



Legende

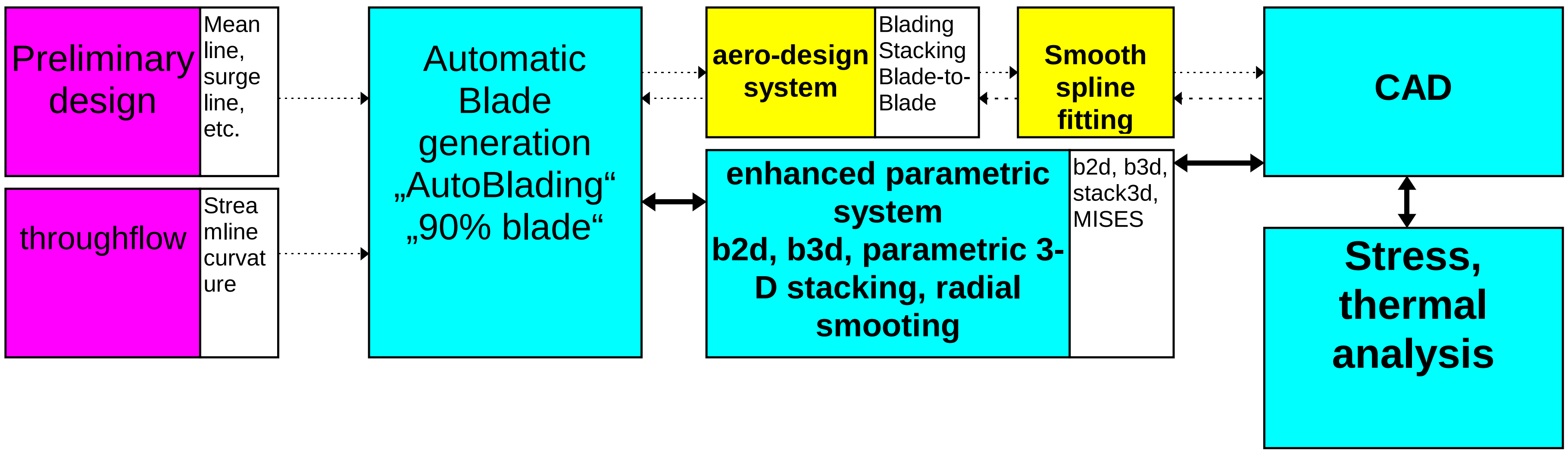


New process



Preliminary design
Mean line, surge line, etc.
throughflow
streamline curvature
Automatic Blade generation „AutoBlading“ „90% blade“
enhanced system b2d, b3d, parametric 3-D stacking, radial smoothing
b2d, b3d, stack3d, MISES parametric
CAD
Stress, thermal analysis
Legende
Transformation with approximation
uniqueTransformation without approximation (1-to-1 mapping)
Spline representation
Nonparametric representation
no blade geometry present
Application program

Combined process



Legende

Transformation with approximation

uniqueTransformation without approximation (1-to-1

Spline representation

Nonparametric representation

no blade geometry present

Application program

Parametric profile editor *b2d*

As a result of the experiences from the ***AutoBlading*** rules-based system and the requirements for a stream-section profile modification tool a new profile editor ***b2d*** has been developed for geometric shape definition and modification of turbine and compressor blades.

Features of *b2d*

The profile editor comprises the following features:

1. 100% compatibility to the ***AutoBlading*** system
2. automatic optimum fit parametrisation of existing profiles
3. smooth blade surfaces
4. 2-D design capabilities
5. improved easy-to-use graphical user-interface
6. improved program reliability
7. parametric curve description with Hermite curves of degree 5
8. read & write to the ***BladeFile*** database, to a parametric database and to external geometry
9. can be used in conjunction with other design tools

Program description

The profile editor uses the same parameter representation of the presentation for the section geometry as the autoblading system. The user is referenced to **part I** of the presentation for more details.

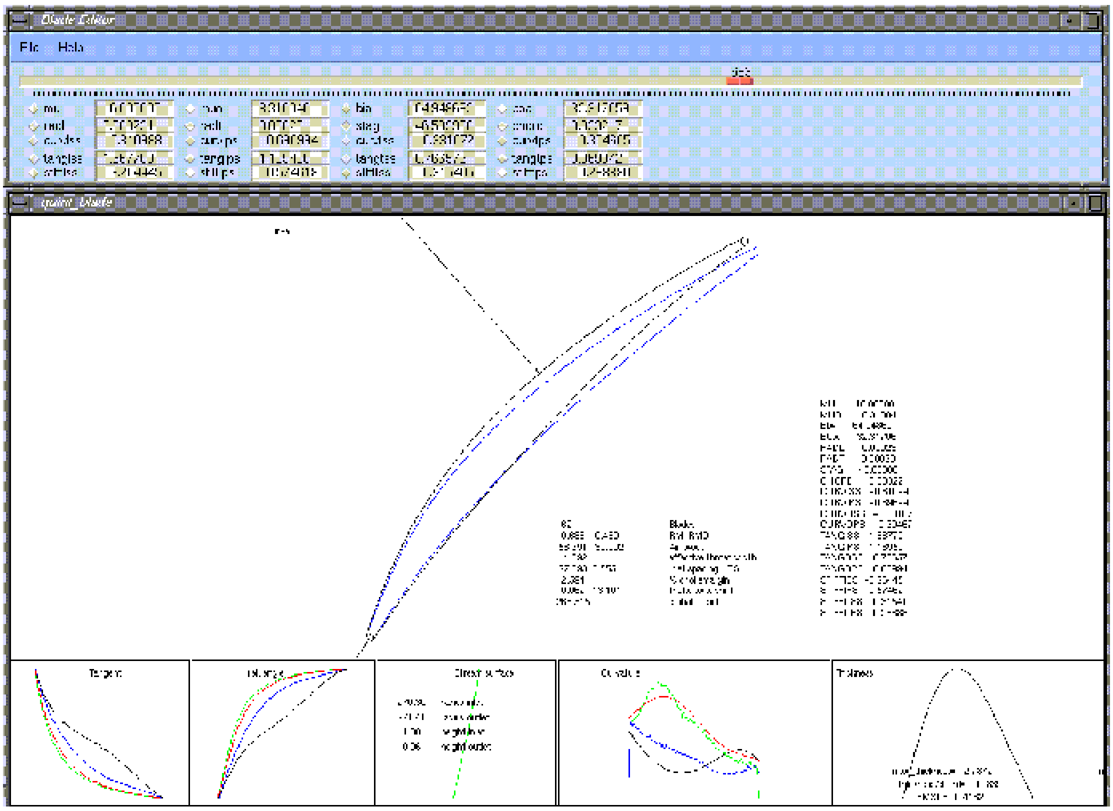


Abbildung 22 Blade profile editor b2d

Basically what the user modifies are parameters like blade inlet & exit angle, blade wedge angles, stagger, chord, tangential length, curvature and stiffness of suction and pressure side curve on both leading and trailing edge. This sums up to a total of 20 parameters. Experience shows that this should be sufficient to meet design criteria for all compressor and LP turbine blades in engine projects relevant for BRR. The will be further investigation whether the same approach can be applied for the more "kinky" HP turbine blades as well.

The main window

The main window consists of a menu bar for read & write options of section geometry, a single scrollbar and a display panel for the parameter values of all 20 section geometry parameters. The use can select an arbitrary parameter by clicking with the mouse on the respective radio button an modify the value by using the slider.

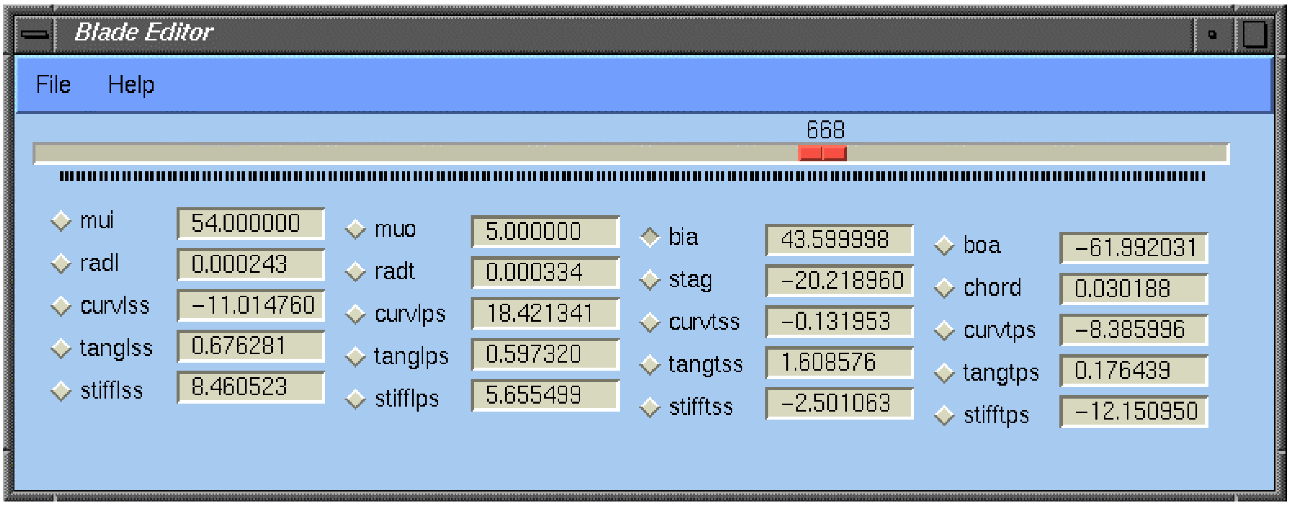


Abbildung 23 Parameter variation in a common scrollbar

The graphics window

The main graphics window displays the original section geometry (blue), the new modified section geometry. Below that tree additional graphics windows display tangent angle, relative angle and curvature distribution of the original and the modified profile for both suction and pressure profile.

Automatic fitting

The input profiles are automatically fitted with an optimum fit procedure based on a non-linear least squares optimisation routine. This means that each input profile (e.g. From DT6 of the BladeFile) will automatically transformed into the parametric description used within ***b2d***. If the system is used in conjunction with the AutoBlading, no fitting is necessary, since the AutoBlading is 100% compatible in the geometry description (it uses the same parameter set).

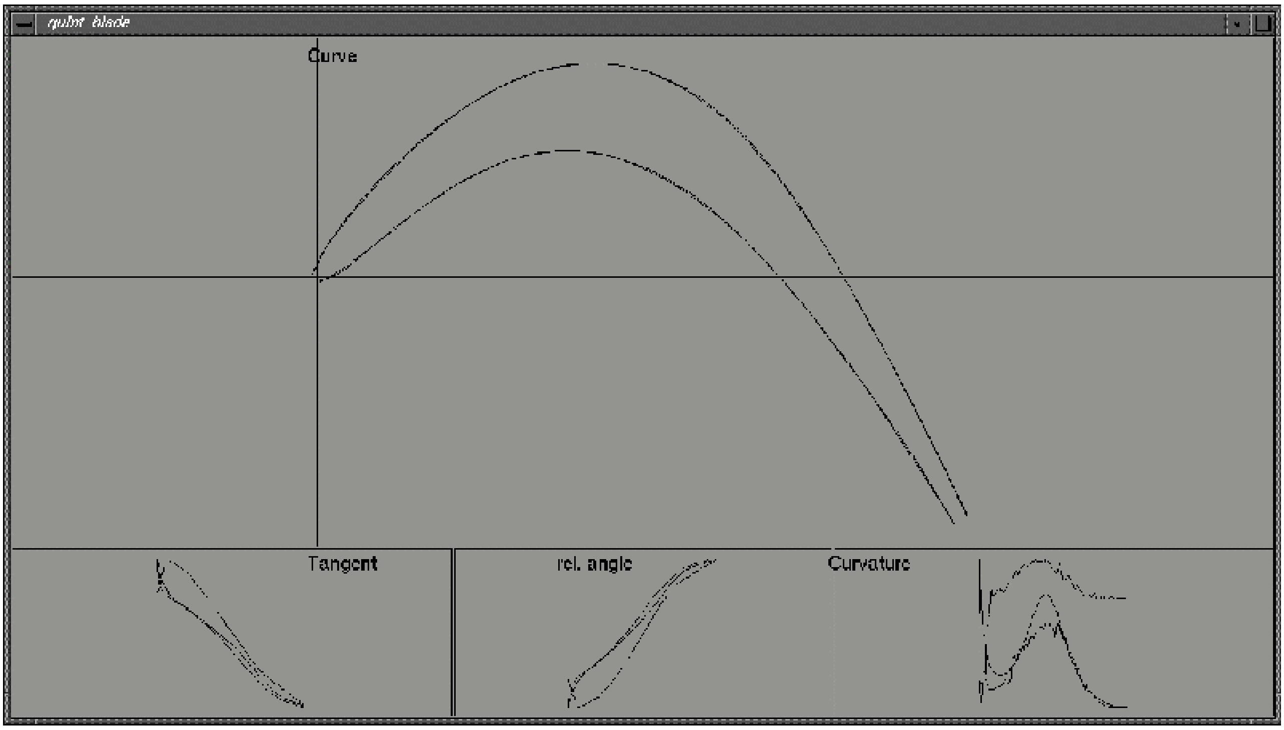


Abbildung 24 Example of profile fitting

Stacking information

The program ***b2d*** treats the section as a translation invariant geometry entity. This means that all geometry parameters are invariant under any form of axial or circumferential shift. The program does not manipulate stacking information of the original DT6 stream section profile on the BladeFile. This means that the stacking point of the original profile will not be moved for any changes of any of the given parameters. E.g. if the chord length is changed and the original blade was stacked on the leading edge, the resulting blade will have the same leading edge stack (=position in 3-D space), but a different shape of the trailing edge.

Use of the scrollbar

All parameters can be varied in real time via a single scrollbar. In order to modify a single section parameter, click with the mouse on the respective radio button to activate the slider for the parameter.
With each parameter is associated a definition interval. The user is only allowed to modify this parameter within the given definition interval.
In order to map the different definition intervals for the different parameters a linear transformation is applied, cf. Table 1.

Parameter	Definitionsbereich	Lineartransformation f=a*x+b: (a,b)
mui number(14,7),	[-5°..180°]	(10,50)

muo	number(14,7),	[-5°..180°]	(10,50)
bia	number(14,7),	[-90°..90°]	(5,450)
boa	number(14,7),	[-90°..90°]	(5,450)
radl	number(14,7),	[0.0002..0.01]	(50000,0)
radt	number(14,7),	[0.0002..0.01]	(50000,0)
stag	number(14,7),	[-90°..90°]	(5,450)
cord	number(14,7),	[0..0.5]	(1000,0)
curvlss	number(14,7),	[-1..1]	(500,500)
curvlps	number(14,7),	[-1..1]	(500,500)
curvtss	number(14,7),	[-1..1]	(500,500)
curvtps	number(14,7),	[-1..1]	(500,500)
tanglss	number(14,7),	[0..2]	(500,0)
tanglps	number(14,7),	[0..2]	(500,0)
tangtss	number(14,7),	[0..2]	(500,0)
tangtps	number(14,7),	[0..2]	(500,0)
stifflss	number(14,7),	[-1..1]	(500,500)
stifflps	number(14,7),	[-1..1]	(500,500)
stifftss	number(14,7),	[-1..1]	(500,500)
stifftps	number(14,7)) ;	[-1..1]	(500,500)

The slider has an definition interval of [0,1000]. The definition interval of the parameter is mapped onto the definition interval of the slider via the linear transformation of table 1. This mapping can be modified by means of an coefficients file ***trafo.dat***. If this file does not exist on the users current directory, it is created with default values valid for compressor cases. Turbine design requires a slightly different transformation file, available from the group directory.

Parametric database

To enable concurrent simultaneous engineering with the parametric blade design system, a database connection for the design data is necessary. It was decided to use latest & best technology for this database. A web-based Oracle implementation of the parametric database was developed for that purpose. The data can be accessed via any Internet-Browser from any machine in the computer network. The solution developed here is based on Oracle’s latest technology and can be used as a prototype solution for the BRR/RR functional database.

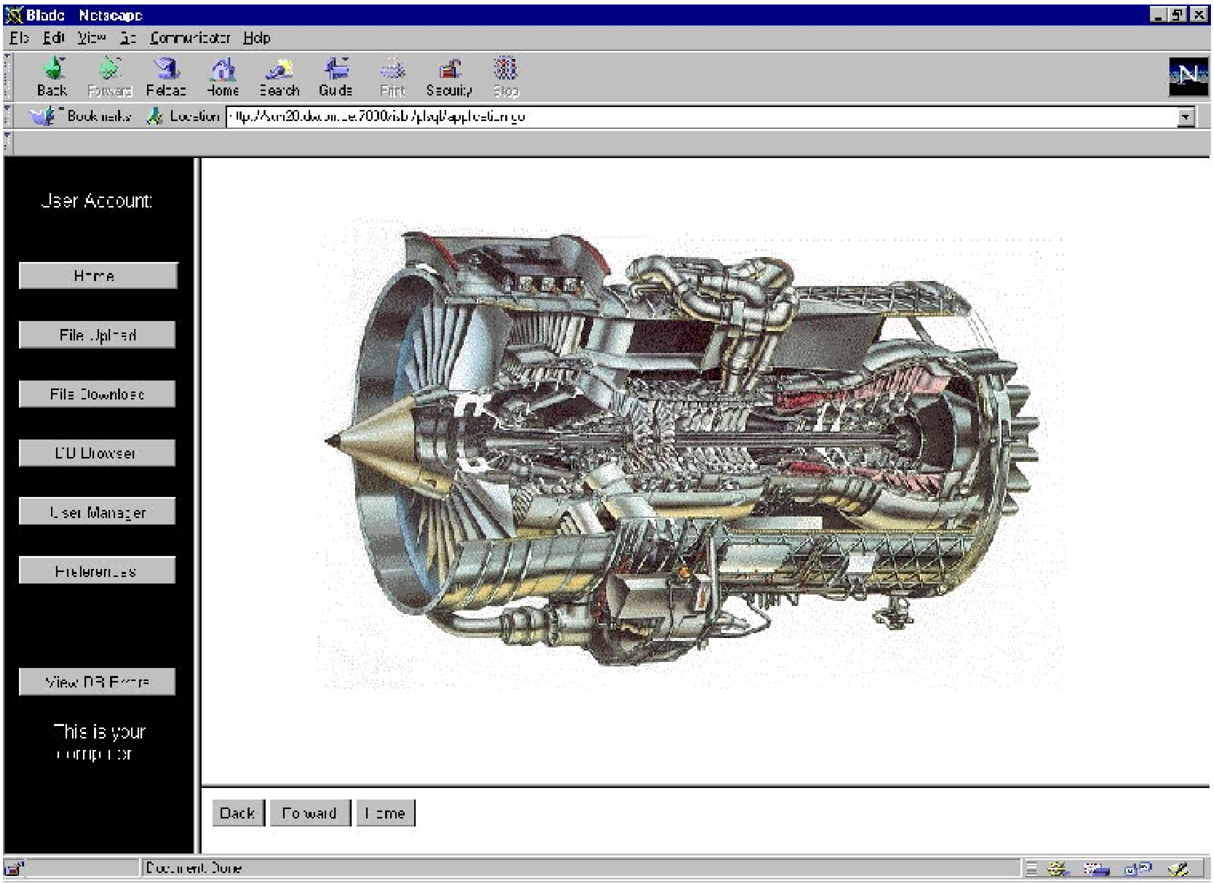


Abbildung 25 Parametric database login window

Details of the specification of the database, the implementation and a user guide are contained in reference 24.

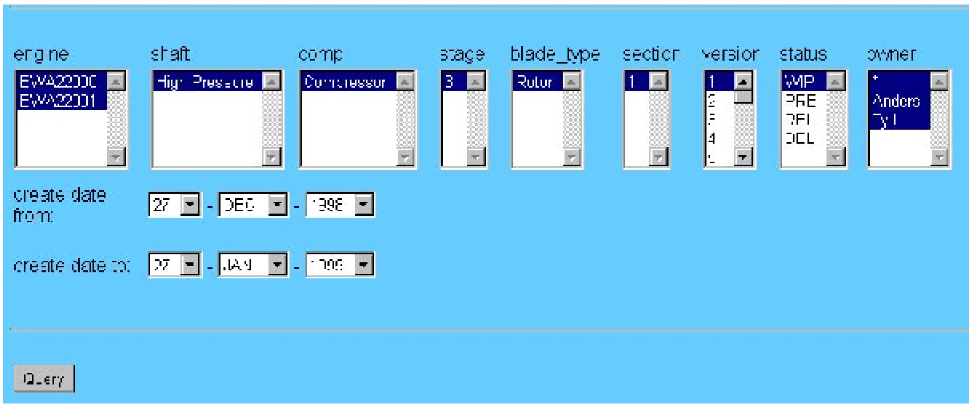


Abbildung 26 Query in parametric database

The database is part of the BRR EDM/PDM solution based on Windchill. It can be viewed as departmental data-mart and part of the company's data-warehouse.

detail view	engine	shaft	comp	stage	bt	section	version	status	owner	create date	last_read	last_update
X	EWA22000	hp	c	3	r	1	1	WP	Admin	11 DEC 98	14 DEC 98	14 DEC 98
X	EWA22001	hp	c	3	r	1	1	WP	Admin	11-DEC-98	--------	--------

Abbildung 27 The result of the query can be viewed following a hyperlink

The database is fully implemented in Internet-technology and allows easy navigation, search, collection and e-mail forwarding of information.

Integration into the 3-D parametric design system

The way the 2-D design tasks for individual sections and the 3-D geometry features are combined and implemented into user-friendly software determines the overall efficiency of the designer's work.

We can see, that for the streamwise and the radial direction different types of parameters have been used in order to implement the users desired options most realistically.

We have now the task to integrate the different philosophies into a single tool with a reasonable user-interface. This interface supports the selective working on the stream section and radial stacking layer.

Conclusions

Blade design technology should no longer be viewed as the companies secret core technology. Parametric representations of profiles and blade stacking enable various optimisation procedures and establish bi-directional data exchange to standard CAD systems on the basis of spline curves, surfaces and solid models. Future trends will very likely show a systematic commercialisation of the standard techniques. Similar to the development in the FEM and CFD area, the basic technologies are relative mature now. Their application is mandatory to maintain design process efficiency and keep leading in the cost-, time and innovation competition world-wide.

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