A Hybrid Redesign Strategy to Derive Load-Adaptive Parts

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ABSTRACT

The meaning of simulation of virtual prototypes has become more and more important over the past years. Corresponding to this is the necessity to manipulate the CAD-parts which represent the basis of those simulations. This article deals with methods to handle virtual models in theory and praxis within the context of a simulation process. In detail an approach for a workflow is presented that enables one to make use of a deformed part in the CAD-environment after successful structural simulation. The advantage of the utilization of such native CAD data which fulfill specific needs with regard to the applied load situation is based on the still precise and parametric definition of the geometry, as there is no approximation through smoothing or similar necessary. One pre-condition is the use of an efficient CAD-software with the ability to create hybrid models. During realization of the approach there are issues of coding and software-interfaces to be taken into account as well as a proper modeling strategy within the context of CAD. Therefore one of the main aspects will be to create a CAD-model in a way that enables loss-free implementation of external data. The approach also increases the available degrees-of-freedom for geometry-manipulation in contrast to sizing- and shape-optimization. In further steps this method is mainly utilized to create load-adaptive parts in an iterative optimization process.

Keywords: CAD, CAO, comprehensive adaptivity, virtual redesign, interoperability.
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1 INTRODUCTION

The use of Computer-Aided Design during the product engineering process has become a standard-tool in many companies. Due to extensive possibilities of modern CAD-software not only members of engineering teams need access to integrated modules, but also employees, who are not primarily involved in the design process itself which represents the core of the implemented modules. Thus generated various views bring up a further need for virtual models: They are not meant to be just a virtual embodiment of geometry but a data-pool, too. Users of such data-pools nowadays are engineering teams, designers, production planners and increasingly operators which are familiar with the simulation of virtual models. An overview on this widespread access is given in Fig. 1.

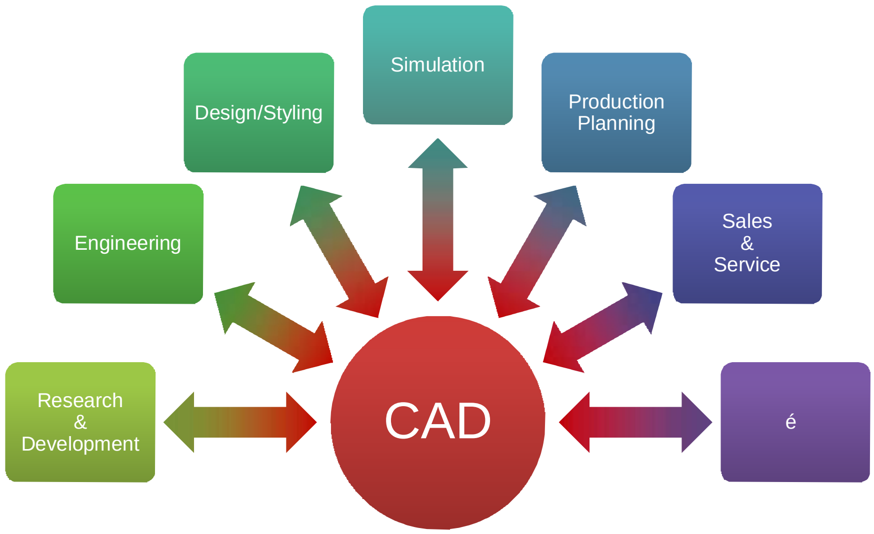


Fig. 1: Widespread interoperability of CAD-models.

In addition to the validation of design-engineering solutions with help of numeric tools those are often utilized to create optimized solutions or at least to make suggestions for alternative designs. This often results in a variation of design-parameters or the modification of the so far developed topological shape. Directly connected to these changes is the need for manual or partly automated geometry adjustment which is caused by solely unidirectional coupling of CAD- and simulation model with its results. These aspects lead to the facts that the resulting shape neither exists in the desired CAD data-format nor shows it a satisfying accuracy of the imported surface (see paragraph 2).

Usual approaches to exchange geometry-data or ðparameters are node- and geometry-based redesign methods. The procedure, as well as advantages and disadvantages of the mentioned options, are picked out as central topic in the following chapter and lead to a hybrid approachwhich is presented in detail in chapter 3. In this context it will be important to make use of a suitable modeling strategy for a parametric and simulation-prepared CAD-model and to implement it into a system independent workflow. Directly connected with this intention is the geometry representation structure which is available in the utilized CAD-software. A shear CSG-structure (Constructive Solid Geometry) is not targeted, as the use of geometric primitives offers too less degrees-of-freedom (DOF) [5]. More flexible features are available, when using a B-Rep-structure (Boundary-Representation), as they can be controlled via splines or else. This results in the fact, that all together the existing data structure and the methodological realization of the buildup of virtual models are closely linked [4].

The universality of the developed approach is supported by the capability of modern CAD-Software which as a rule contains programming environments (API = Application Programming Interface) to realize interfaces and couplings to external data or software. Furthermore there is no limitation to defined simulation disciplines. The resulting deflections are calculated with a FE-software which also provides measures for the redesign, so that the geometry is òdrivenó by the results. The source of the loads for the simulation is completely independent from the approach, so that a coupling of further tools such as Multi-Body Simulation (MBS), Computational Fluid Dynamics (CFD) and Thermal etc. supports the intended universality. Aim of the whole process is a part-model close to reality which deflects under an applied load and assumes a defined ideal shape.

The following chapters pick out the state-of-the-art concerning methods of redesigning in the context of CAD as a central theme and introduce the above mentioned hybrid approach which is detached from specific software.

2 STATE-OF-THE-ART REDESIGN STRATEGIES

Currently applied methods for the re-construction of simulated geometry mostly utilize the discretized mesh-structure or access before defined and during the solver-run manipulated design-parameters ð such as radii or distances ð to visualize the optimized geometry. Further options are offered by data formats like VRML, IGES etc. which make use of a facetted illustration of the optimized geometry and create system-neutral model data. Other approaches generate 2D-projection views out of point-clouds to identify and create geometric primitives with dedicated algorithms, so that the result is a CSG-structure [7] or they alter parameters of B-spline curves to manipulate part-models [11] (Fig. 2).

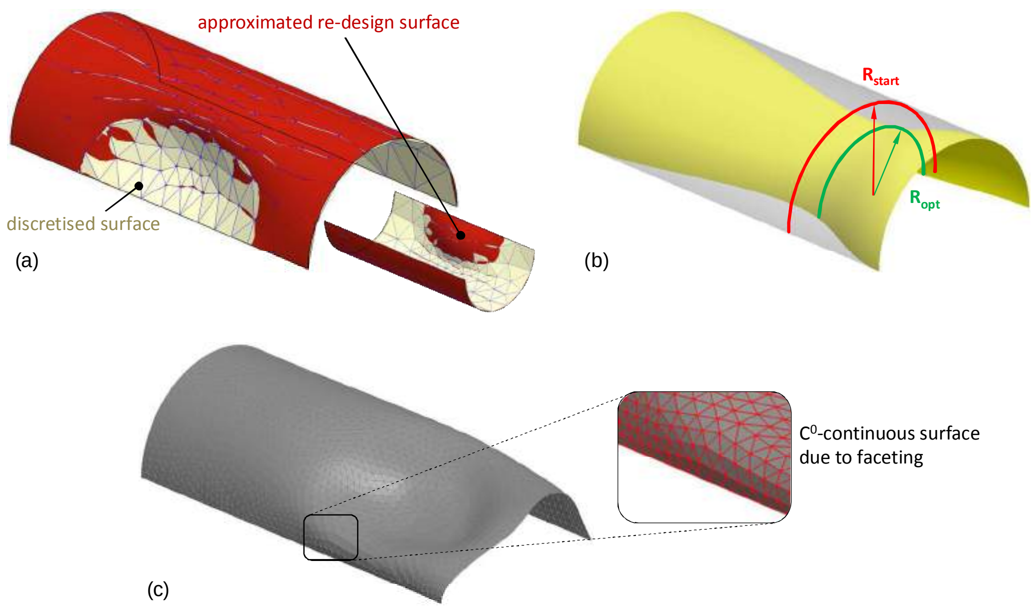


Fig. 2: Virtual redesign: (a) Node-based, (b) geometry-based and (c) VRML model.

A re-construction of such virtual models into native CAD-Data often turns out to be quite complex in addition to the expenditure of time despite the existence of available tools for surface-smoothing and (partly) automated identification of simple features (feature-recognition) such as holes, rounds and chamfers. By using the mentioned methods, the designer knowingly accepts an approximated shape of a surface as final result. Anyway a better result is possible with more precise mesh-settings. Dependent on the intended purpose of use this accuracy can be sufficient.

In the following passages commonly used methods and examples of applications of redesign based on mesh-nodes and design-parameters are presented.

2.1 Mesh Driven Redesign

Node-based geometry re-construction is mostly used as reverse-engineering method after topology optimization respectively shape generation, as in this case the mesh is explicitly manipulated; geometry is re-adjusted according to the variation of the mesh. This specific simulation discipline aims at a geometry optimized with respect to mass and stress-distribution according to known loads and constraints. Topology optimization usually uses a 2D or 3D optimization-domain as its design-variable to which the simulation algorithm has access to [1]. Within this domain numeric FE-simulations are performed iteratively until a solution according to user-defined constraints and goals is achieved.

During the solver-runs the density of mesh elements is varied corresponding to calculated stress-results. When the solving process is finished elements under a defined boundary value for the density are hidden so that a load and mass optimized geometry can be visualized. The result is a very coarse and broken up topology with gaps and singularities (Fig. 3).

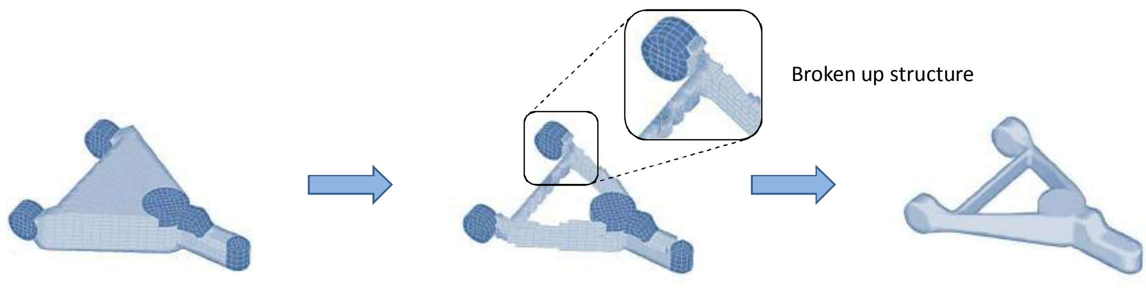


Fig. 3: Typical topology optimization process.

Such shaped surfaces are not qualified for subsequent use during production planning or other connected processes. The foundation for the necessary surface-smoothing is build by mesh-nodes which are positioned right at the surface. For the re-construction into a CAD-model 3D-scans can serve as source, too which is a current practice in medical engineering. By smoothing point-clouds via automated algorithms free-form surfaces are created which as a rule are technologically and economically not feasible from the view of production [6]. An advantage of this method is in fact that by using mesh-nodes for the definition of a surface many degrees-of-freedom are available, so that the whole topology can be manipulated [11]. A limitation concerning the number of nodes and for this reason the accuracy of the surface is primarily based on distinctive increasing solver-time.

Alternatively a manual redesign is also possible. Here the design-engineer has some room for interpretation, so that according to experience for this approach no explicit design can be predicted. On the other hand abstraction on notional level and manual recreation provide an opportunity to react on production relevant aspects and to implement a company's guidelines into system-internal features. At the same time this procedure is very time consuming and leads to subjectively affected results instead of objective ones because of the individual style of the involved design-engineer (Fig. 4).

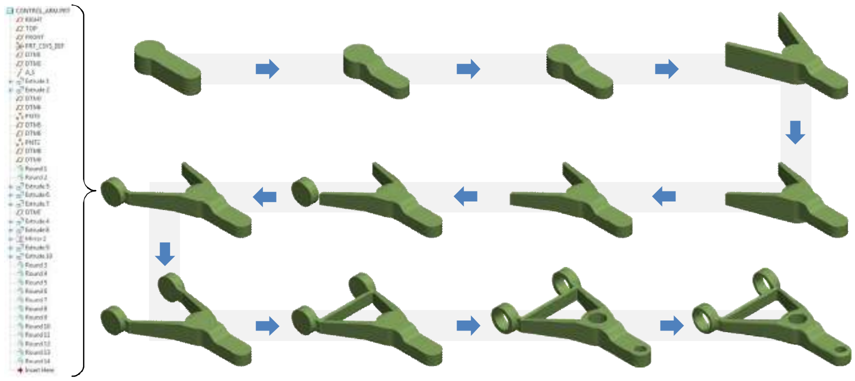


Fig. 4: Example of manual redesign of a topology optimized geometry.

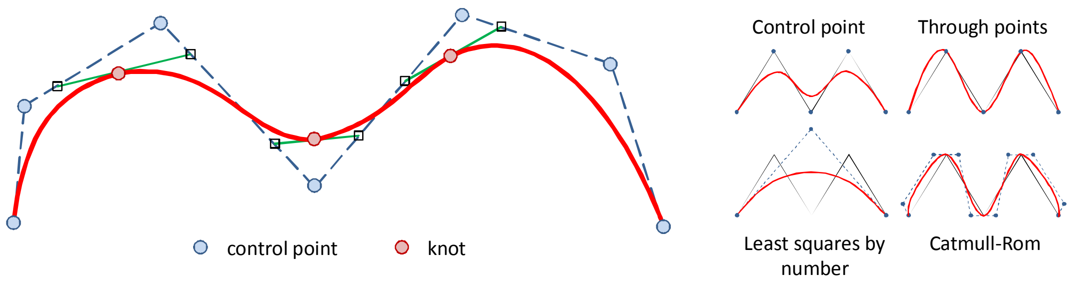
Strategies to support the manual re-construction process are e.g. orthoscopic projections of an existing point cloud in multiple view-directions. With this help the designing-engineer has a direct reference to the result and is able to create an enclosing shape with respect to needs of production, that is close to the optimized geometrical specification. Other approaches make use of mesh-nodes close to the boundary to derive curves which have to be smoothed first and then serve as references for cross sections in surface- or volume-oriented modeling strategies. In the case of simple shapes this process can be executed automatically to identify and generate geometric primitives like spheres, cylinders and cubes etc. [4], [5], [7], [9], [10].

To put it in a nutshell, the transformation of node-based geometry into a virtual model ð accessible by native CAD tools ð is not satisfactorily solved, yet. In addition with the inevitable loss of accuracy of the redesigned surface these points arise the necessity for more sophisticated strategies at least for chosen branches in engineering.

2.2 Geometry Driven Redesign

Beside the node-based reconstruction of simulation models the parameter-based redesign is also a capable method to represent an optimized topology. Yet the main focus of attention is targeted at the variation of an existing topology to optimize certain characteristics. Therefore this approach is classified as shape or sizing optimization, where design-parameters of the simulation-model are used to manipulate the parts shape; the mesh is òdrivenó by geometry changes. One requirement is a parametrically robust and adaptable start model with the necessary degrees-of-freedom. In addition to these DOFís expedient specifications and limits have to be set. The optimization algorithm iteratively decides by means of before determined optimization goals (stresses, mass, deflection é) which variations have to be made to the available design-parameters until a proper configuration is obtained. Geometry based topology optimizations can be ð as long as necessary modules are available ð performed within a CAD-system itself as well as in isolated external expert systems which have to contain corresponding CAD-features.

Necessary methods for the system internal description of geometry (CAGD = Computer Aided Geometry Design) have been investigated in numerous researches and are exposed to constant updates due to increasing possibilities in modern CAD environments. Beside the utilization of simple features like rotation- and sweep-bodies and their connected dimension-parameters such as radii, thicknesses and distances etc. which form the topology in an appropriate combination it is also possible to make use of modeling strategies which involve flexible curves e.g. splines and their enhancements. In contrast to curves from polynomials of a higher degree which maybe cannot be described with mathematical equations within a CAD-system, one has the possibility to utilize certain control parameters to create very flexible curves which can be varied by re-positioning of control points respectively control polygons. Depending on the intended use there already exist adopted approximation strategies (Fig. 5).



(a) (b)

Fig. 5: B-Spline Curves: (a) Geometric creation and (b) approximation variants.

Furthermore such B-spline curves do not tend to oscillate, as it is known with polynomials of higher degree. At the same time there is C^0-, C^1- and C^2-continuity directly connected with the characteristics of B-spline curves, what makes them very useful for the design of surfaces with optical demands. Significant algorithms for the application in technical environments ð especially for CAD and other graphical-based software ð have been established in the 1960ís by Bezier and de Casteljau. Later they were extended by Ferguson and de Boor [2] and are utilized even today because of their mathematical robustness and good applicability within program codes. Most of all the possibilities offered by NURBS-curves (Non-Uniform Rational B-Splines) increased the adaptability and flexibility of virtual models enormously.

In CAD-systems integrated simulation modules use the advantage of exclusively internal interfaces for the transfer of parameters and data during shape- and sizing-optimization processes as there is no loss of information. The coupling of external software for the extension of the spectrum of a simulation means more effort and preparation to reach this loss-free transfer sufficiently. In the general case without a direct interface between CAD- and external software, data-files mostly represent the only possibility to transfer external created data into a CAD-model (Fig. 6).

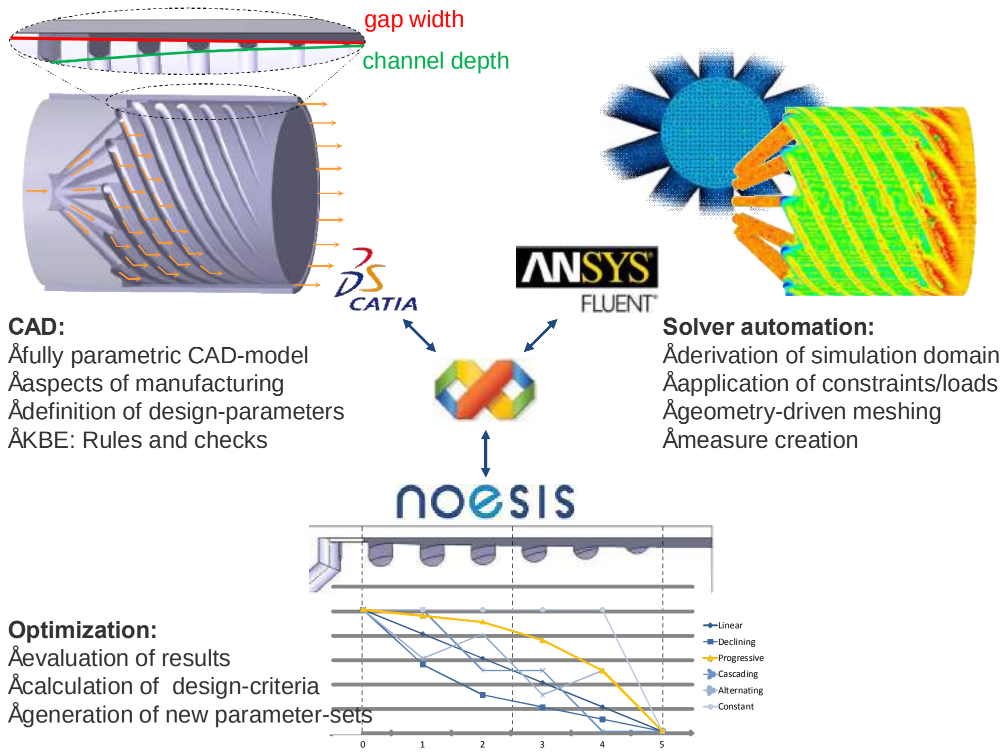


Fig. 6: Shape optimization with respect to improved flow behavior.

The displayed example is based on results from a DFG (Deutsche Forschungs-gemeinschaft = German Research Fund) supported project, where the coupling of CAD and CFD was used to generate spiral-mandrel-tools with respect to an improved flow-behavior and manufacturing restrictions [8]. A start geometry based on design-data was given, so that the decision in favor of the method of geometry-based topology optimization was obligatory. Detailed optimization of flow relevant features was then executed with defined design-parameters as mentioned above and with help of methods from the field of Knowledge-Based-Engineering (KBE) to implement rules important for the process and the models robustness. An evaluation of the simulationôs results and the connected parameter-set was performed with self-defined criteria which were transferred into one single criterion to judge on the quality of the past iteration. The interaction of a parametric robust CAD-model and its role as data-basis within an automated optimization process is shown in Fig. 7.

Direct manipulation of CAD-geometry with integrated tools provides very good results as well as the presented coupling of various tools in the context of automated shape- and sizing-optimization with following geometric redesign. The result is an adjusted ð yet undeformed ð geometry in native CAD-data which can be the basis for subsequent steps e.g. documentation for manufacturing processes within the standard workflow [3], [11].

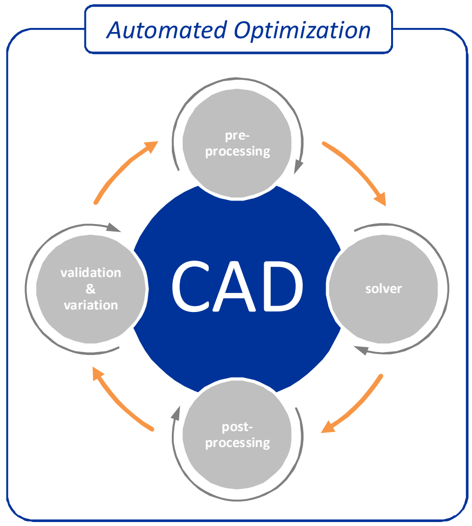
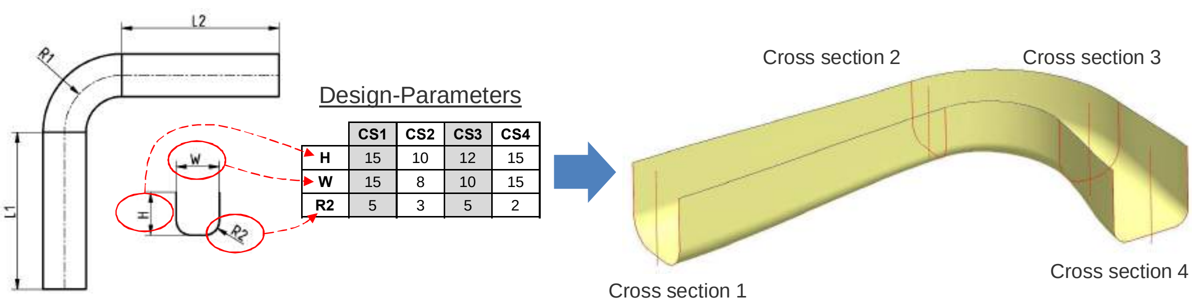


Fig. 7: Central role of a CAD-model within an optimization process.

Own completed research projects and experiences proved, that the DOFs in typical parameter-optimizations are limited. As only single parameters are manipulated which can of course affect the flexibility in collaboration with a smart modeling-strategy, the adaptability is not always sufficient. One deficit often comes up with cross-sections which are fixed in their topology and only behave geometrically stable within certain limits (Fig. 8). Algorithms for the automated substitution of cross-sections or the use of geometrical checks are dependent on the utilized CAD-software and do not always serve the intention of higher robustness satisfactorily.



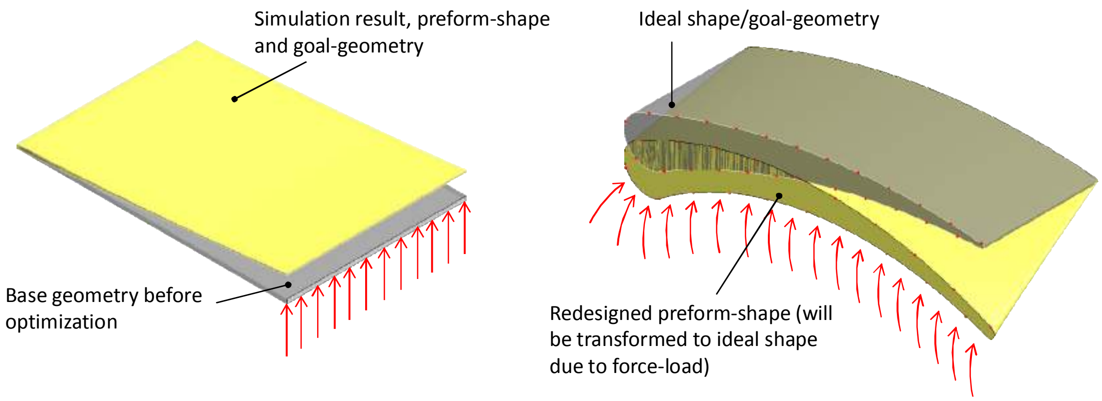
	CS1	CS2	CS3	CS4
H	15	10	12	15
W	15	8	10	15
R2	5	3	5	2

Fig. 8: Limited degrees-of-freedom in the context of sizing-/shape-optimization.

So for geometrically challenging cases more sophisticated methods have to be considered respectively developed to reach the goal of geometry based and at the same time geometric flexible re-construction of simulation data into native CAD-data. Where possible applications may be situated and how such model-/data structures can be realized on basis of coupled CAE-features is shown in the following chapter.

3 APPROACH ON RESULT-DRIVEN GEOMETRY REDESIGN

The problem of reconstruction of simulated models has been investigated over the past years which resulted in various feasible methods. Most important approaches have been introduced and discussed in the previous chapter. Following a combination of these two approaches is developed which aims at the creation of load-adaptive parts. With such kind of models respectively real world parts different goals can be pursued. One possibility is to run a simulation until a balanced state is reached and then transferring the result into a CAD-model. Such parts can e.g. be the basis for tolerance- or assembling-analyses (DMU = Digital Mock-Up). This kind of support enables the early identification and solving of problems caused by deformation (Fig. 9 (a)). The extension of this approach leads to the pursued objective: Based on an ideal start-geometry which was designed for a special purpose, an iterative optimization is executed so that finally a systematically deformed topology is generated which is meant to reach the ideal state under an applied load (Fig. 9 (b)).



(a) (b)

Fig. 9: Utilization of intentionally deformed parts.

In consequence of the available ideal start-geometry which serves as basis for this process, the approach has to be correlated with the well-known discipline of shape-/sizing-optimization. At the same time it is aimed for the independence from certain software so that any combination of suitable software-tools is possible.

3.1 Geometry Definition with Comprehensive Feature-Points

The implementation of this idea is based on the fusion of the geometry-based model-generation by using parametrically controllable curves and the redesign with help of simulation results and point coordinates, as it is done according to the node-based redesign method. By employing the advantage of system internal curves, surface-smoothing which is directly connected to node-based methods, becomes dispensable. Anyway feature-points are necessary for the definition of the outer shape of the virtual model, as their coordinates as a first step serve as parameters to control and update the desired geometry. Furthermore these points perform a comprehensive influence on the connected process steps, so that they represent a kind of òbackboneó for the optimization process (Fig. 10).

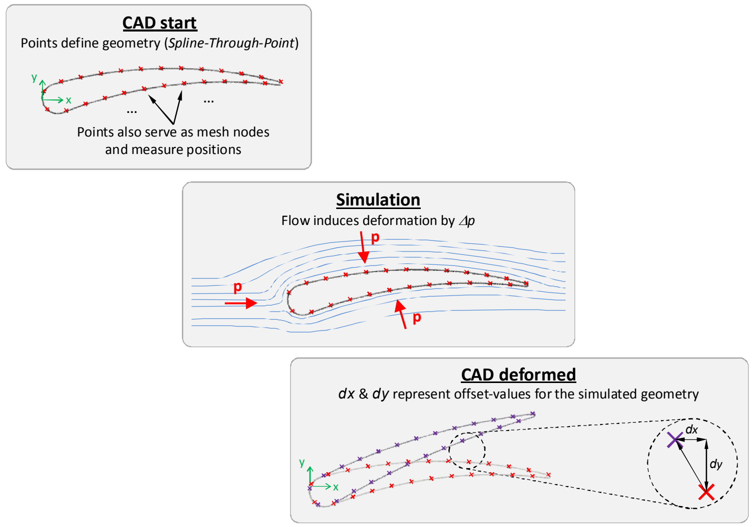


Fig. 10: Hybrid redesign with comprehensive feature-points.

The geometryís source can be data from external expert applications which calculate contours and points under certain demands and needs. To implement these shapes in a parametrically robust virtual model splines offer expedient possibilities. Those are available in all performant CAD-systems and can be controlled and kept flexible by imported points respectively point-coordinates. A variation of curve-specific parameters like weighting is not executed, so that for a first try the option òspline-through-pointsó is utilized. This is a common practice, as during design processes often points are calculated which are positioned right at the surface of the designed part. To obtain a coincident approximated curve more operations would be necessary to calculate control polygons. The proceeding for the creation of a spline, parameterized with control polygons, would be dependent on the used CAD-software which leads to a limitation of the intended universal approach. So using feature-points as comprehensive control-instances becomes obligatory, as with their help geometry is defined, meshing can be directed in a desired destination and post-processing benefits from directly connected deflection-values. The topology respectively the geometric cohesion is always secured and native CAD-data are available for further processes.

At this point it should be remarked that the intention is not to create complete CAD-models with this approach, but to a greater degree important functional surfaces or single components which interact with other features that are not subject to optimization.

3.2 The Process of Result Driven Redesign

The planned optimization is going to be an iterative and automated process which has to couple multiple software-packages. As necessary interfaces are not given, a data-transfer has to be realized for the entire approach. The demands on these data-interfaces are moderate at the beginning, as only simple data-files have to be managed. In further steps more efficient file types such as XML could be subject of interest to serve as data-base which would result in an upgrading for the whole process. This data exchange which involves all interacting software-systems, can be done in a sub-routine which is part of a master routine. The tasks for this master routine also imply the sequential execution of involved software. This deviation from the universality is in this case inevitable, because otherwise no closed loop for an optimization can be generated.

The entry point into the optimization and redesign process is a parameterized and ideal-shaped CAD-model based on external data, in this case point-coordinates (Fig. 11).

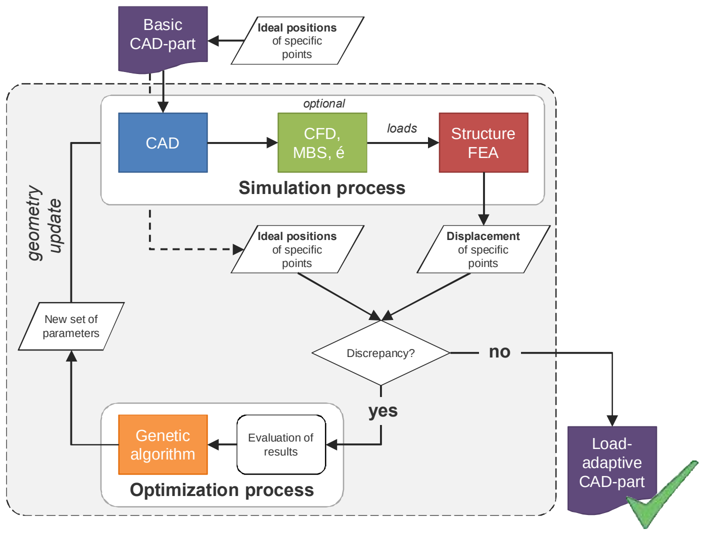


Fig. 11: Load adaptive parts as result of an iterative redesign process.

For the pre-processing, the part-model is transferred to the suited software, where beside the application of loads and constraints the discretization into finite-elements is performed, too. Here the first correlation of the comprehensive feature-points takes place, as the CAD-points serve as mesh-nodes, whereas h- as well as p-meshes can benefit from such points during automated discretization. Depending on the capabilities of the chosen solver it might be necessary to create measures at these points which record the nodes displacements. With reference to the automated and universal character of the approach, this step has to be implemented with help of macros or other coding depending on the available API, as manual interaction should be avoided. The calculated node-displacements represent the basis for the post-processing of FE-analyses, as in combination with material parameters further measures are derived. In the general case every node has three translational and three rotational degrees-of-freedom. The translational displacements are stored in a data-file and in a following sub-routine compared with the ideal positions from the start-geometry. When a discrepancy is calculated which also represents a termination criterion and therefore affects the quality of the results, those are transferred into a sub-routine which evaluates them according to the intended goals. A self-developed optimization algorithm then creates a new set of point-coordinates which is then sent to the CAD-system for a geometry-update. The decision for a suitable type of algorithm can be cut down to a target-aimed way of coordinate-manipulation, as only one solution respectively solution-interval exists. A random selection of parameters, as it is done e.g. with the Monte-Carlo-Algorithm, is therefore not an appropriate way. The result of the update is a pre-formed model which serves as geometric base for the next iteration steps. As the topology did not change, no actions have to be undertaken for pre- and post-processing, as references for load etc. stay the same. After an undefined number of iterations with the loaded model, the discrepancy between displacement and ideal-shape is within a certain limit, so that the optimization-loop is terminated; further process steps with an intentionally deformed virtual-model are possible.

4 CONCLUSION

In this final paragraph, the so far more or less theoretical approach is carried over to possible practical applications. The method is not to be seen as solely academic, as among other things the optimization of parts applied with flow induced loads can benefit from this approach: It is possible to create topologies which are designed for one specific or maybe multiple operating points, as the compensation of the relative deformation allows for parts which work close to the optimum within an applied flow. Hence e.g. the efficiency of pumps and compressors can be increased which directly affects the operating costs in a positive way. Commonly used measures to stiffen a design then become subsidiary: The component does not have to be kept in an ideal state, as it aligns itself under load to reach this state. Practical tests on real world parts are meant to validate and verify the conversion of the introduced method.

From the processȁs point of view it will have to investigated, whether an extension of the intended point-based method makes sense and how it can be applied. For specific parts there will be the challenge to keep a defined correlation between these points, as e.g. a blade-contour should be a blade-contour after optimization as well. One aspect could be studies concerning capabilities of direct-modeling which is an ascending technology in the CAD-environment by now, as there e.g. extended result values like torsion angles could be utilized for redesign actions. Anyway all these and further explorations are subordinate to the aspiration of independence from specific software.

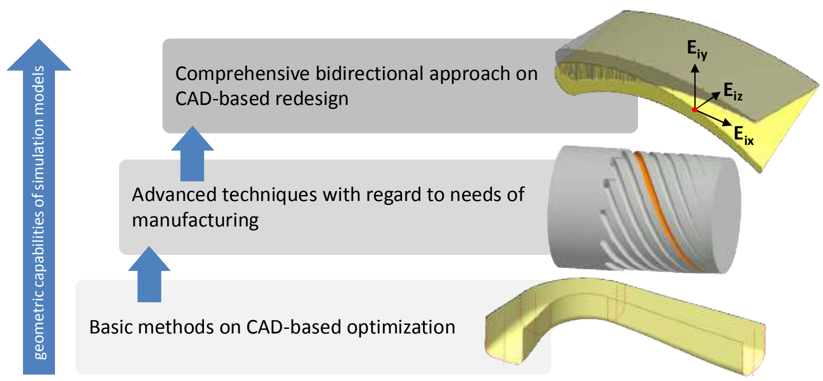


Fig. 12: Development of CAD-based optimization.

The posed issues summarize the state-of-the-art of techniques for virtual redesign and introduce a combined approach for a coupled optimization process. Furthermore the potential for practical use of this approach was presented. The method is a consequent continuation of passed research projects from the Department of Computer Aided Engineering at University Duisburg-Essen (Germany) which also dealt with CAD-based optimization and led to important experiences and results (Fig. 12).

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