Free-Form Shape Optimization using CAD Models

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1 Motivation

The current state of the art in shape optimization is dominated by approaches utilizing computer-aided design (CAD) to manipulate the shape under consideration. On the contrary, free-form shape optimization approaches have not reached the same industrial acceptance, although for example the Vertex Morphing Method showed with many practical problems promising characteristics like high optimization potential, minimum modeling effort or fast design space exploration (see e.g. [1], [2]). One major reason for this limited popularity of free-form shape optimization techniques is their missing link to CAD being the primary design tool in many industrial branches. More precisely, while it is common practice to discretize an initial CAD-model so that a numerical optimization may be performed, it is far from trivial to reconstruct a CAD-model once the discrete optimal design is found - unless the original CAD parametric is used to modify the shape in the first place. The latter, however, depending on the case, may limit the optimization significantly. In the following, we present a novel workflow which may close the existing gap between free-form shape optimization and CAD.

In this workflow, we follow an automatic approach to transform results of a free-form shape optimization process back to CAD so that a CAD-model of the optimized geometry is available. We thereby make use of the fact that in CAD workflows the geometry to be optimized is initially given in CAD-format. Creating a CAD model of the optimized geometry hence may be regarded as a mapping operation instead of a pure design task. This is different as e.g. in topology optimization and allows a significantly better automation. Also, we exploit the fact that the geometry to be modeled by CAD is already known. It corresponds to the given optimization result. So, we may analyze the latter to for example estimate number and position of necessary control points. Note, that this is still different to the case that a CAD parametric was used in the optimization. Here the choice of the parameters severely influences the optimal solution possibly leading to an expensive re-parameterization or an unconvincing objective improvement.

Using the herein presented workflow, free-form shape optimization may be effectively linked to CAD, so that the full potential of free-form shape optimization may be exploited also in a CAD-based design process. In the subsequent chapters, we briefly discuss the complete workflow along with selected process steps and individual aspects regarding process quality and practicability.

2 Free-form shape optimization using Vertex Morphing

One basic process step of the herein presented workflow is the actual free-form shape optimization. Generally, there are different methods for what is commonly understood as free-form shape optimization. One well-known method for example is to use morphing boxes to control the shape during the optimization, [3]. Another established method is to use directly the surface nodes of the analysis grid for the corresponding morphing process. The particular method, which is applied within the scope of this work, is of the latter type and is referred to as the Vertex Morphing Method, [4].

The Vertex Morphing Method unifies shape control, mesh regularization and sensitivity smoothing in a single formulation. Integral part of the Vertex Morphing Method is a local filter operation, which allows to explore different local minima by a single parameter, i.e. the filter size. The filter operation moreover is used to control the surface continuity during the optimization. Hence optimal designs may reach a high geometric quality over the surface.

Result of the Vertex Morphing Method is an optimized geometry given as discrete model (e.g. as a triangulated surface). That is, in a CAD environment a CAD model of this optimized geometry needs to be reconstructed.

3 CAD reconstruction of free-form optimized designs

Another integral process step of the herein presented workflow is the CAD reconstruction. As is explained in section 1, the CAD reconstruction of free-form optimized designs can be regarded as a mapping operation. Input of this mapping operation is:

1) the initial CAD-model (represented by NURBS),
2) a corresponding surface discretization (using e.g. finite elements),
3) and a vector-field describing the shape change from the initial to the optimized design for each node in the discrete surface model.

Using these inputs, a linear mapping equation is formulated. This equation maps the known nodal shape changes of the discretized surface (vector field of displacements) to the control points of the initial CAD model, such that the deviation between the discretized surface and the surface described by the modified CAD model is minimized. Hence, the unknowns for which we are solving in the linear equation, are displacements of the control points of the CAD model. Furthermore, to consider continuity requirements over trimmed edges or patch borders, boundary conditions are applied. Following techniques from the field of isogeometric BREP analysis (IBRA), see [5] and [6], these boundary conditions are enforced weakly using either a penalty or a Lagrange approach.

In fact, the complete mapping operation may be regarded as classical isogeometric BREP analysis of the initial CAD model with a right-hand-side vector that collects information about the position change of the optimized discrete surface. Consequently, we subsequently refer to this mapping as isogeometric BREP mapping. We note, that CAD reconstruction represents a whole new field of application for the IBRA technology - a field of application beyond a pure structural analysis it was originally developed for.

4 Novel shape optimization workflow

Given Vertex Morphing as the free-form shape optimization technique of choice, and the above described isogeometric BREP Mapping for the CAD reconstruction, the individual steps may be combined and integrated into a complete CAD-based design process. Such a process is exemplarily presented in Figure 1 for a simple rapid prototype part.

In the beginning, there is a design problem, i.e. the current design of the structures is too soft and shall be stiffened. Additionally, from the designer we are given the original CAD model. As indicated in the figure, the parameters or control points of the original CAD model (seen as black dots) are not suited for an effective optimization, since obviously, they are accumulated around the boundaries so that probably important shape modifications in the surface center are not possible or only unwanted boundary movements appear. This limitation calls for a manual introduction of alternative parameters for the optimization, which leads to a fundamental problem: the possible optimal designs are not know a priori, so that any suboptimal parametrization may yield unsatisfying results and in the worst-case lead to an expensive reparameterization.

Instead of a possibly limiting parametrization, we want to explore the design potential and seek for maximum design freedom. Consequently, we use all surface nodes of the finite element model as controls for an automatic shape optimization. This is done using the Vertex Morphing Method. The only additional parameter we need to specify with this method is a filter size, which we choose such that high frequent surface oscillations are excluded. The resulting design of such an optimization is depicted in Figure 1. This design has a 100% decreased compliance (100% increased stiffness) compared to the original design and shall be basis for further design steps[1]. To this end the optimized design needs to be reconstructed as CAD model.

Figure 1 shows the result of a reconstruction using the isogeometric BREP mapping described above and obviously, the reproduced surface matches the optimized discrete model without any visible differences. Note, that before the reconstruction, additional control points were introduced in the original CAD model, which explains the increased number of control points arranged in a grid pattern over the reconstructed CAD surface (black dots). These additional control points where necessary to actually allow a representation of the given “curvy” design, since clearly the original set of control points is not

[1] Note that, if the result of the optimization for some reason was not acceptable, we could change the filter size and re-run the optimization. An expensive reparameterization is, however, omitted.

able to do so. Indeed, introducing these additional control points is very much like choosing parameters in a CAD optimization process. But different as in the latter case, it does neither require any knowledge about the optimization nor an understanding of the entire design process. The only knowledge it requires is, how to refine a CAD model (by inserting knots for example) so that a known shape modification may be reached by an automatic movement of the control points. This is a task, which, compared to the actual optimization, fits much better into the activity profile of a classical design department.

We would like to emphasize that this novel shape optimization workflow not just allows to introduce the advantages of a free-form shape optimization into a given CAD-based design process, but also facilitates the distribution of competences or separation of tasks within such a process. More precisely, to allow for a later shape optimization, the designer does not need to consider any optimization aspects during the design phase. Instead he could just outsource the complete (free-form) optimization to a specialized department, wait for the outcome and subsequently tune the original CAD model such that the now known optimal geometry may be reached in an automatized mapping process.

Also, we would like to emphasize that, because of this clear separation of tasks, any free-form shape optimization may be applied to come up with an improved design. That is, even so we prefer to use the Vertex Morphing Method, also other techniques may be used to perform the optimization. As long as the resulting geometry may be expressed in form of the inputs described in section 3, the isogeometric BREP mapping may be applied to reconstruct a CAD model of this resulting geometry.

After all, the reproduced CAD model may be used for further steps downstream the design process or to finally produce the design. A 3D print of the optimized design is also presented in Figure 1. Clearly, the optimal design behaves much stiffer and hence solves the original design problem.

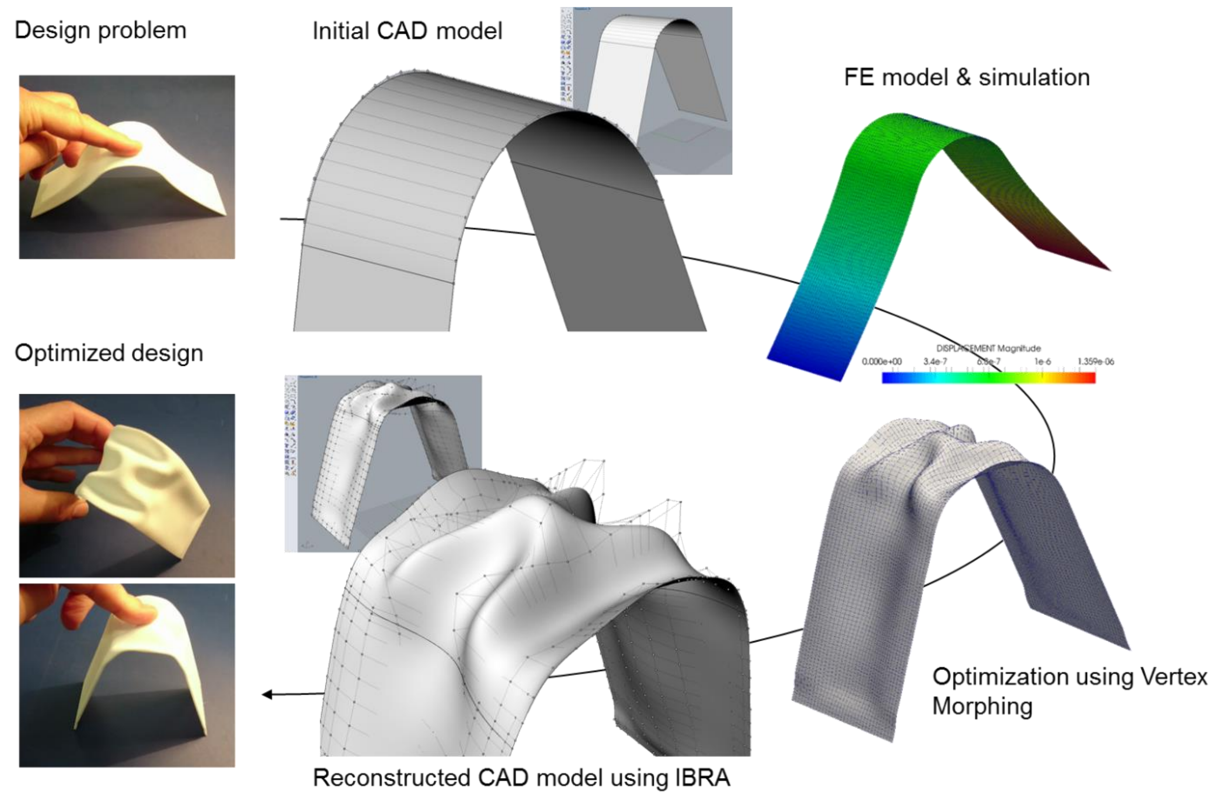

Figure 1: Workflow for free-form shape optimization using CAD-models

5 Quality of the CAD reconstruction

Given the CAD reconstruction as is done in the above described workflow, one may question the geometric quality of the reconstructed models as well as its influence on the optimization results.

5.1 Geometric quality of the reconstructed CAD models

The isogeometric BREP mapping by construction may produce high quality geometries with a surface continuity of up to any implemented degree (given that the surface possesses the corresponding polynomial degree in both parameter directions in the first place). According to the current state of research, however, it is only possible to maintain G0 and G1 continuity. That is, given the original model is (fully or partially) G1 continuous, the reconstructed will be so, too. Figure 2 indicates the geometric quality of a reconstructed model of a generic optimization example.

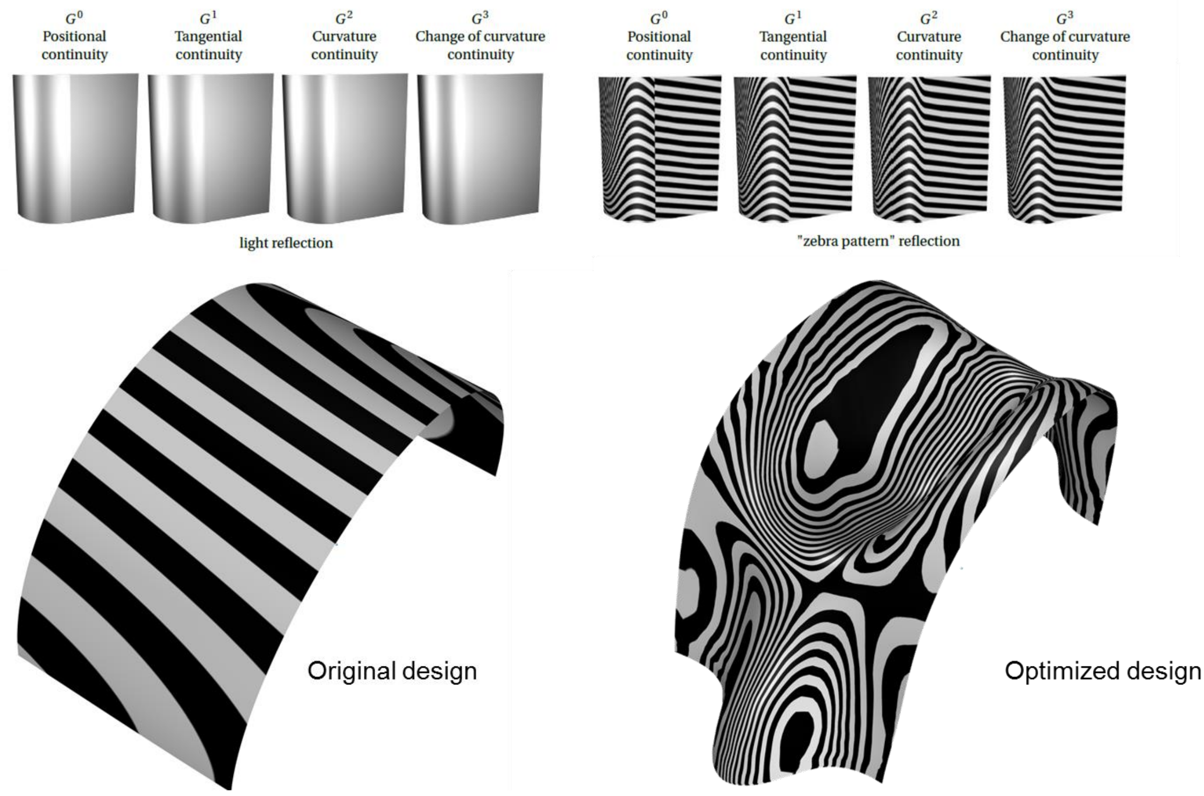

Figure 2: Light reflection pattern (light lines or "zebra plot"), showing the surface quality of a generic optimized design

In the future, it will also be possible to maintain continuities up to G2. Furthermore, we will develop techniques to enforce G1 or G2 even if both is not reached in the original model. That is, the isogeometric BREP mapping will not just be used to reconstruct a CAD model, but also to simultaneously improve the model quality.

5.2 Influence of CAD reconstruction on optimization results

One way to quantify the quality of the reconstructed CAD model is to compare the response function values before and after an optimization. Figure 3 shows such a comparison for a volume constrained compliance minimization (stiffening) of a crane hook.

Herein, the optimization of the discrete model using Vertex Morphing showed a 24.00% compliance improvement after the final design was found (figure center). In comparison to that, the compliance values associated with a discretized model of the original design (left value) and a discretized model of the reconstructed design (right value), show an improvement of 24.01%. That is, the reconstructed CAD model shows practically the same performance improvements as the optimal design found in the free-form shape optimization process. This means, the reconstruction is consistent and along the way, we maintain the significant improvements suggested by the free-form shape optimization process. As a matter of fact, the slight deviations in the percentages above are only because discretizing the optimal CAD model leads to a different discretization compared to the one given after the optimization and before the reconstruction.

Figure 3 also shows, that the CAD model of the optimal design indeed holds practically the same volume as the original design. So, the optimization algorithm does not just fulfill the constraint, but also the CAD reconstruction did not degrade this quality criterion by a practically relevant amount.

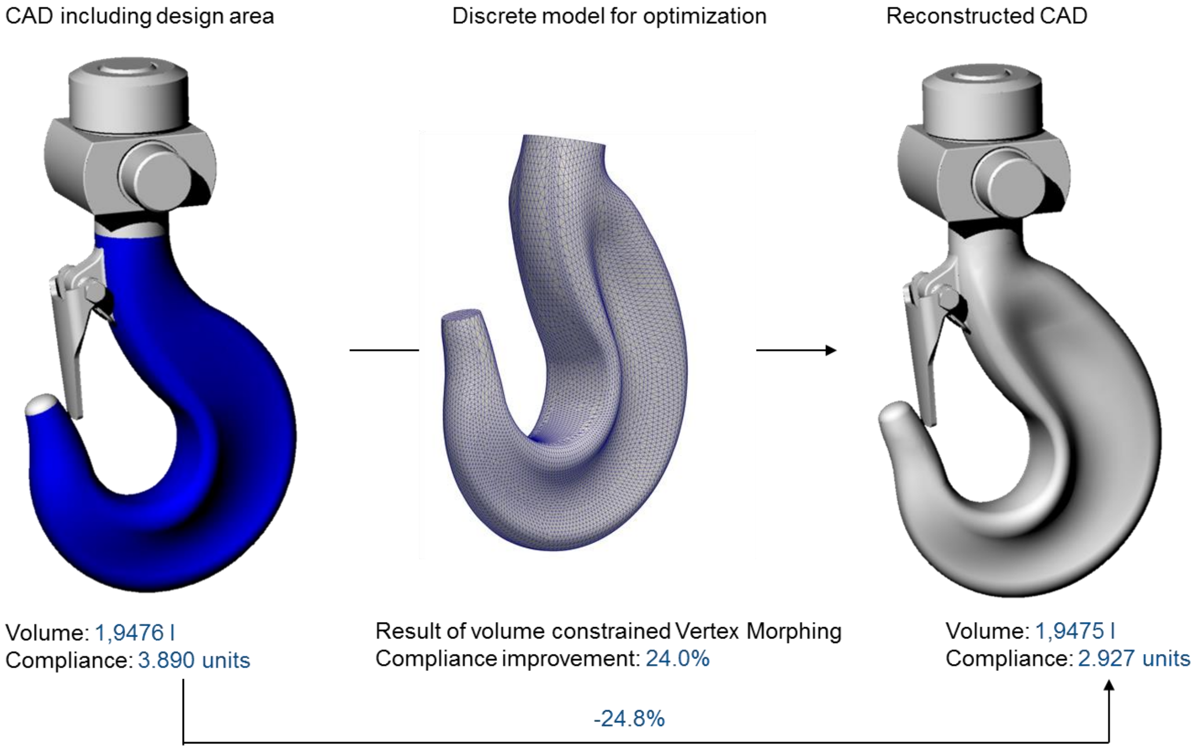

Figure 3: Comparison of response function values before and after the volume constrained compliance minimization of parts of a hook using Vertex Morphing and CAD reconstruction

6 Practical aspects of free-form shape optimization using CAD models

First practical aspect, we would like to emphasize is, that the workflow described above is not limited to specific geometries or smaller examples. In fact, other applications show that it may be successfully applied in more complex scenarios, too. An example from another design optimization process is indicated in Figure 4 and Figure 5. Figure 4 shows parts of the numerical model of an aircraft, which was to be optimized for drag keeping lift constant whereas the complete surface should be controlled in a free-form shape optimization process using the Vertex Morphing Method. The optimization resulted in a significantly improved overall design, particularly also in areas which before could not be optimized using CAD parameters directly. The improved overall design was then reconstructed in CAD using the original CAD model and isogeomeric BREP mapping, see Figure 5. The reconstructed model eventually shows some of the core design modifications proposed by the optimizer (like e.g. an improved section around the wing attachment). The reconstruction is used for further analysis downstream the corresponding preliminary design process.

Another practical aspect we like to emphasize is the fact, that the CAD reconstruction may be not just done at the end of the optimization but also iteratively after every optimization step. By that, a CAD model is available for the complete optimization history, which may be exploited to increase the process robustness. For example, having a CAD model of the surface under consideration may facilitate a possibly necessary re-meshing at a specific optimization step due to a failing mesh-regularization algorithm. Without CAD model, such an intermediate re-meshing becomes very challenging and is hence prone to failure. On the contrary, having a CAD model available the re-meshing mostly corresponds to the meshing done at the beginning of the analysis and optimization, which likely is even automatized already.

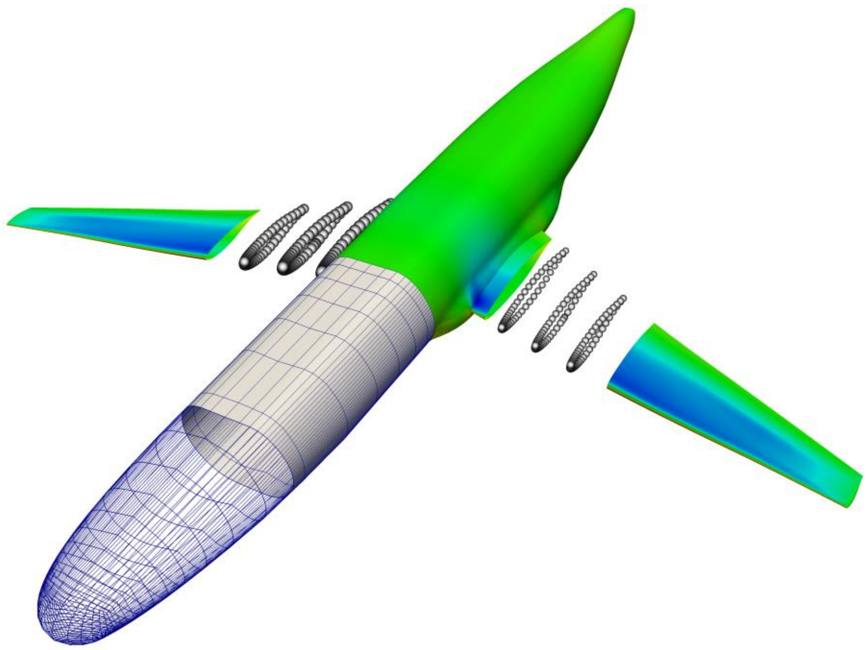

Figure 4: Surface grid and superposed distribution of the pressure coefficient for a given aircraft

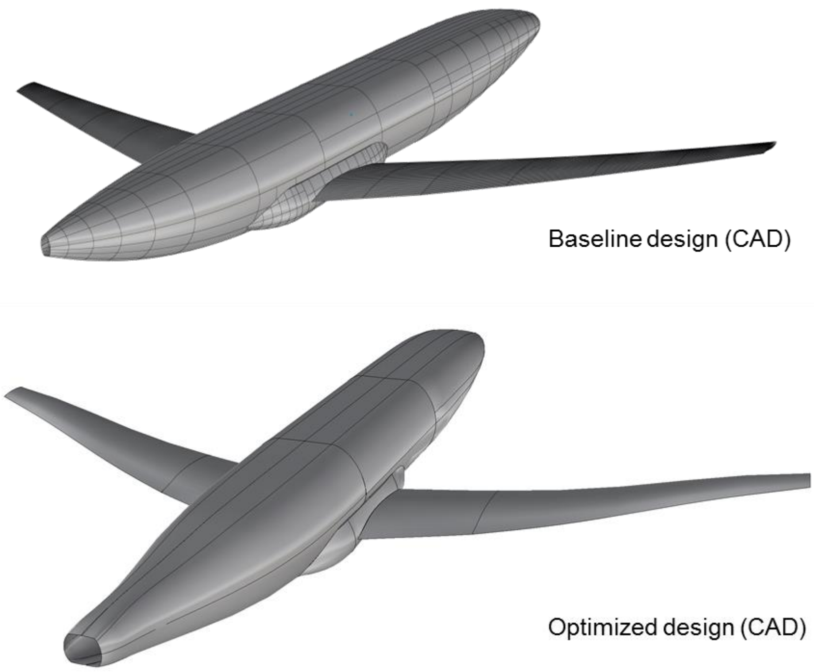

Figure 5: CAD reconstruction for free-form shape optimized aircraft

7 Summary

A novel workflow that seamlessly integrates free-form shape optimization into a CAD-based design workflow was presented. As an integral part of this workflow, we showed a feature to reconstruct CAD models from the results of a free-form shape optimization process. Therefore, we utilize techniques from isogeometric BREP analyses. As particular free-form shape optimization method, we in this work chose the Vertex Morphing Method because of its inherent capabilities in terms of exploration of the design space. Given the ability to reconstruct CAD models, we are now able to bridge the gap between free-form shape optimization and CAD, so that all the advantages of such a free-form optimization process may be exploited in a pure CAD-driven design workflow. Individual aspects of such a workflow were demonstrated for different examples.

8 Literature

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