Title:

Morphing Boxes for the Integration of Shape Optimization in the Product Design Process

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Introduction:

Shape optimization software provides valuable input during the design of mechanical product parts. Employing mathematical algorithms, it methodically and efficiently improves an existing product's design geometry with respect to user-defined criteria. Typical examples include weight minimization or the maximization of a stiffness measure under weight restrictions. The main obstacle in utilizing shape optimization results often lies in the fact that these are mesh-based, as the algorithms commonly manipulate a given Finite Element (FE) model. Ultimately, they should be applied to a Computer-Aided Design (CAD) model. One basic strategy to achieve this, which is employed in the industry, is a conversion of the optimized FE mesh surface to a new CAD model, for example, by approximating the former by an IGES wire grid model or an STL model. By replacing the original CAD model, however, the underlying construction logic is lost, impeding further design modeling following the optimization.

A more promising approach is to bridge the gap between FE mesh-based optimization and CAD by applying the same method for parameterizing shape changes to both. Various methods of geometry parameterization for shape optimization have been proposed [9], some even mentioning possible applicability to CAD modeling. The most notable is the use of Isogeometric Analysis (IGA) [3, 12]. While IGA seems promising for this and other purposes, it has yet to be established in the commercial and industrial setting. With a focus on practical applicability in the industry, so-called morphing boxes are employed in this paper, constituting an interface between commercial CAD software and optimization tools.

Main Idea:

Background: Shape Optimization

A shape optimization problem is a special type of structural optimization problem in which only the surface of the product design is optimized [5]. It can typically be defined mathematically as

$$\min_{\vec{x}\in\mathbb{R}^n} f(\vec{x}), \quad \text{such that} \quad g_i(\vec{x}) \le 0,\ i = 1,\dots,m\,. \tag{1}$$

Here, f is called the objective function and g_i are the constraint functions. The components of $\vec{x}$ are the design variables. These are the variables that parameterize the product design. Since effective shape optimization software commonly works with an FE model, the design variables are defined so as to determine the displacement of mesh nodes. Tosca structure in particular defines a design variable as the displacement value of a "design node" which is a mesh surface node allowed to move during the optimization. To iteratively find a solution to (1), the sensitivity-based Method of Moving Asymptotes (MMA) is employed [10]. The term "sensitivity-based" indicates that the sensitivities, i.e., the derivatives of f and g_i with respect to $\vec{x}$ are used in an algorithm, which, for the general case, gives it better convergence properties than, e.g., a heuristic algorithm. The sensitivities are computed within Tosca structure.

Morphing Boxes

The idea of morphing boxes has been explained in Perry et al. [6]:

“Consider a cube of clear, flexible plastic, in which several objects have been embedded. The embedded objects have the same degree of flexibility as the cube. As the plastic cube is deformed, the embedded objects are also deformed in an intuitive manner.“

The main contribution of this work is to use morphing boxes to parameterize that part of the product design geometry that is to be changed within the optimization – in the FE model as well as in the CAD model. In this way, they provide an interface by which the FE mesh-based optimization results can be applied to the CAD model. In the optimization step, the morphing box parameterization is coupled to a sensitivity-based optimization algorithm, which is crucial when considering efficiency.

In this work, morphing boxes have been implemented as B-Spline volumes, as has previously been done in [2]. More specifically, they are defined by

$$[0,1]^3 \ni (r,s,t) \quad \mapsto \quad \vec{V}(r,s,t) := \sum_{i=0}^{I}\sum_{j=0}^{J}\sum_{h=0}^{H}\vec{c}_{i,j,h}B_{i,k}(r)B_{j,l}(s)B_{h,m}(t)\,, \quad I,J,H \geq 1\,, \tag{2}$$

where $B_{i,k}$ is the *i*-th B-Spline basis function of order *k* for a uniform, open knot-vector spanning the interval [0,1] with no repeating inner knots. (For details on B-Splines, see [7]). The 3-dimensional grid of control points $\vec{c}_{i,j,h}$, herein called control polygon, defines the morphing box volume and thus the shape of the embedded object – which, in this case, is the design to be optimized. The morphing box's initial geometry is not restricted to a cube, but is fairly flexible, and is in the following merely assumed not to be self-intersecting or singular. Continuity constraints at the box's side faces are imposed by fixing the corresponding layers of control points. An illustrative example of a morphing box is shown in Figure 1.

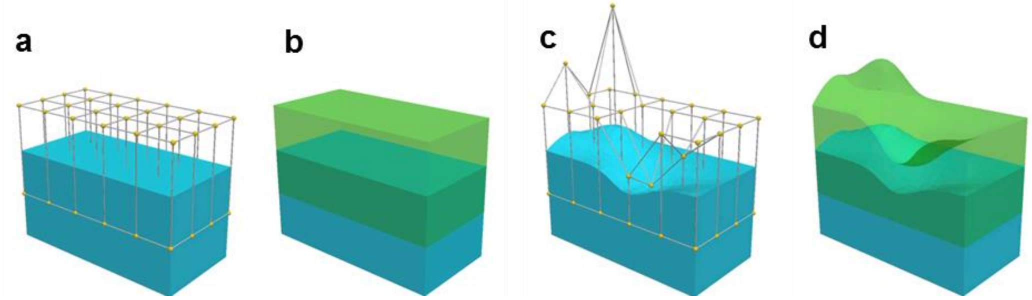

Fig. 1: Simple morphing box (green), defined by a control polygon (grey), for manipulating a simple design geometry (blue): (a) and (b): Initial morphing box and design; (c) and (d): Changed control polygon, resulting morphing box and morphed design.

Morphing boxes in Tosca Structure

To realize the embedding of the FE model in a B-Spline volume morphing box for the purpose of shape optimization, the control points $\vec{c}_{i,j,h}$ are now defined as the design variables. Design nodes are redefined as all nodes within a morphing box, including inner nodes of the mesh, and their dependency on $\vec{c}_{i,j,h}$ has to be determined. Then, Tosca Structure can perform an optimization on the control points instead of directly on the design nodes. A modified Newton's method, implemented in Python, is used to determine the design nodes and, for each such design node $\vec{x}$, obtain local coordinates (r,s,t) which satisfy $\vec{V}(r,s,t)=\vec{x}$, with $\vec{V}$ defined in (2). Thus, the linear relationship between $\vec{c}_{i,j,h}$ and the design nodes' coordinates becomes known, which Tosca Structure requires to calculate the sensitivities. The Python program writes out this information in the form of a matrix M, which is read in by Tosca. After the optimization, optimization increments for the control points $\Delta\vec{c}_{i,j,h}$ are put out.

Morphing boxes in CATIA V6

Current CAD software does not offer a morphing box tool as described above. Therefore, it has to be emulated by using a series of existing tools. A consistent workflow has been derived which closely mimics the functionalities of a B-Spline volume morphing box, but which imposes certain restrictions on these functionalities. The CAD system used for the presented results is CATIA V6. The utilized tools and the restrictions they entail are briefly laid out below.

It is not possible for the user to create a B-Spline volume in CATIA V6. Instead, subdivision surfaces [1] are used to model the top and bottom faces of a B-Spline volume. These are surfaces which are defined by 2-dimensional grids of control points. While not mathematically identical, a subdivision surface closely approximates a bi-quadratic B-Spline surface defined for the same set of control points, given a reasonable control point density. The B-Spline volume which corresponds to the two subdivision surfaces in CATIA is defined by the two layers of grid points of these subdivision surfaces. These grid point layers define the top and bottom face of the volume, respectively, which are bi-quadratic B-Spline surfaces. The latter are interpolated linearly to construct a volume. Accordingly, the polynomial orders of the basis functions for the B-Spline volume in (2) are $k=l=2, m=1$.

The operation of deforming that section of the product design which is embedded in the morphing box along with this same morphing box is realized by two tools used in sequence. For two sets of subdivision surfaces, one representing the morphing box in its initial state, the other in its deformed state, the “deviation analysis” tool computes displacement fields for the deformation of the top and bottom faces. This deformation field is used as input for the “digitized morphing” tool which applies the deformation to the embedded section. To guarantee a mathematically correct interpretation of the deformation, in accordance with the morphing box represented by the subdivision surfaces, the following restrictions must be adhered to: Firstly, the initial morphing box must be a rectangular parallelepiped. Secondly, control points may only be moved orthogonally to their initial plane.

The thus-implemented morphing operation is performed not directly on the design part but on a section cut out of this part by a Boolean intersection with the morphing box volume. This section is reinserted after morphing. This is to ensure that the design domain defined by the morphing box is just one of many features of the product design, which can be morphed, replaced or removed without otherwise interfering with the part’s construction logic. This “cut-and-replace” procedure is illustrated in Fig. 2.

Morphing box definitions can be imported into CATIA by defining the control polygon in the Wavefront OBJ format [3].

Process Chain CAD-FE-SO

So far, morphing boxes have been discussed with regard to their use within the individual processes of CAD and shape optimization (SO). To provide a complete treatment of them as a means of integrating SO into product design, a consistent workflow needs to set up, linking these processes and describing the transition from one to the next in the form of a process chain. This process chain is modeled using the Structured Analysis and Design Technique (SADT) and a simplified version of the concept is illustrated in Figure 3. The definition of process chains in the context of computer-aided tools and the product development process can be found in [11].

The implementation of morphing boxes in CAD systems such as CATIA is a challenging step since conversions between different geometric representations are necessary. It is thus required that all parameters changes on the product design achieved during the optimization steps are propagated to the next ones without conflict. In order to achieve a consistent and correct CAD model of the resulting product design, a process chain containing all necessary steps of CAD, FE and SO is established. It is modeled using the Structured analysis and design technique (SADT) and a simplified version of the concept is illustrated in Figure 3. The definition of process chains in the context of computer-aided tools and the product development process can be found in [11].

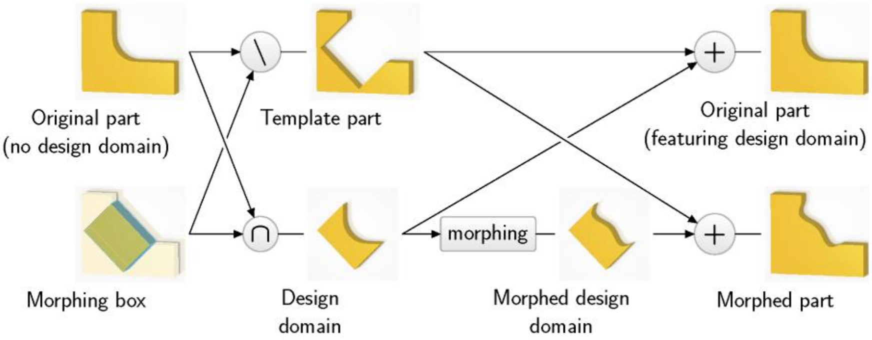

Fig. 2: Defining the design domain as a morphable feature of the part by the “cut-and-replace” approach.

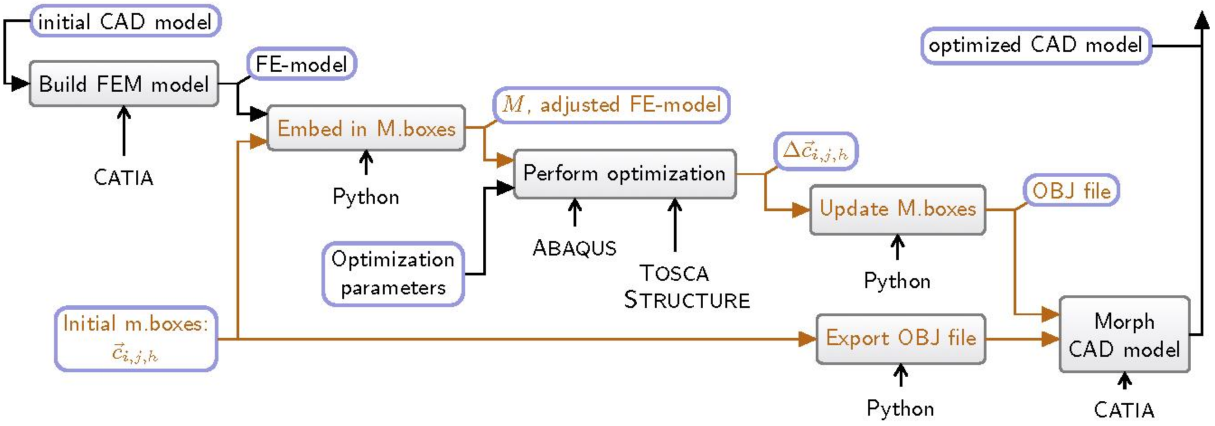

Fig. 3: A simplified Structured Analysis and Design Technique (SADT) diagram for the process chain CAD-FEA-SO.

Test Cases and Validation

The volume v of a piston-engine connecting rod, seen in Figure 3(a), has to be minimized in this example. Quantities relating to material failure and stiffness are constrained. The FE model is geometrically linear and its material behavior is defined as isotropic, linearly elastic. Four load cases are defined for the rod, in which it is stretched along, compressed along, twisted around, and bent orthogonal to its longitudinal axis, respectively. The critical system responses which are constrained in the optimization are the maximum von-Mises stresses of the first and second load case, $\max\sigma_{M,1}$ and $\max\sigma_{M,2}$, respectively, the angle ω of rotation around the longitudinal axis in the third load case, and the displacement u of the load point in the fourth load case.

The morphing box setup is illustrated in Figure 3(b). Control points are fixed where necessary to maintain point continuity or tangency in the product design. Maximum displacement values are defined for the control points in the optimization, but the results remain well within the allowed ranges.

For the optimization problem, the constraint functions are defined so as not to allow the above-mentioned system responses to increase by more than 20% of their value in the initial model. In an actual industrial optimization, a 20% increase of stress peak values or displacements would be considered unacceptable. However, geometric restrictions apply to the morphing boxes that can be modeled in the CATIA V6 workflow, as mentioned in the previous subsection. Hence, the optimization needs to be granted a certain amount of leeway in order to produce a sufficient product design change to validate the overall approach by.

The morphing boxes and mesh after the optimization in Simulia Tosca Structure are shown in Figures 3(c) and 3(d). The optimal morphing boxes are imported to CATIA V6 where they are used to morph the CAD model. A new FE model is created based on this morphed CAD model to validate the optimization results. The change in volume and system response values of the Tosca optimization results and those of the morphed CAD model are both shown in Table 1.

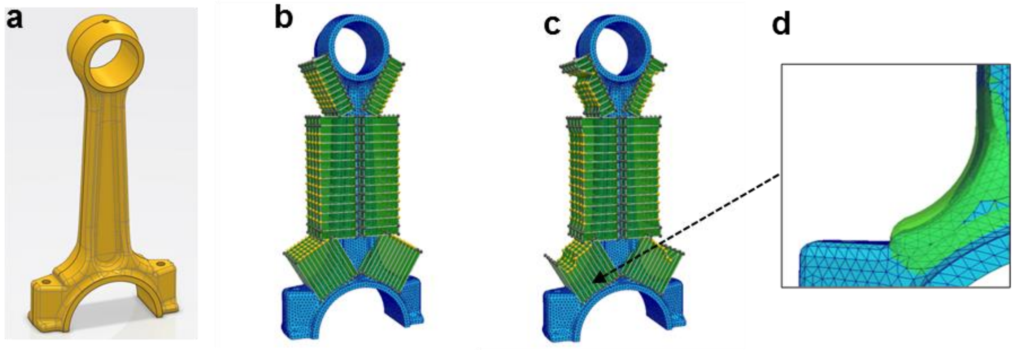

Fig. 4: Connecting rod. (a): Initial CAD model; (b): Initial FE model and morphing boxes; (c): Optimized FE model and morphing boxes; (d): Optimized lower left leg, (initial shape super-imposed in green).

	Design response	Tosca Structure morphing result	CATIA morphing result
Objective function:	v	- 4.18 %	- 3.28 %
Constraints:	$\max \sigma_{M,1}$	4.78 %	- 12.21 %
	$\max \sigma_{M,2}$	20.00 %	12.38 %
	ω	14.51 %	13.02 %
	u	20.00 %	18.25 %

Tab. 1: Change in volume and critical system response values, after the shape optimization and after approximating the shape changes in CATIA V6. Values are relative to the values of the initial model.

Conclusions:

Using morphing boxes, FE mesh-based shape optimization results have successfully been applied to a CAD model. The feature- and history-based construction logic of the model is not overwritten and the original model can be restored easily, as the morphing box operation adds just another feature to the model which can be changed or removed. Furthermore, morphing boxes offer a quite intuitive way of marking out a design area. Also, continuity constraints are easily defined. In order to reconstruct the optimized shape more accurately in the CAD model and to exploit the full potential of morphing boxes as a parameterization method, proper B-Spline volume morphing boxes should be implemented in the CAD environment. This would allow further studies to sound out the limits and possibilities of this approach for an integration of shape optimization into the design process.

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