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A generic approach to capitalize manufacturing experience in design and optimization

Philip Eyckens[1,*], Frank Naets[2,3], Elke Deckers[2,3] , Eveline Rosseel[1], Hendrik Schuette[4], Ioanna Koutla[5], Reginald Diltoer[6], Carlos Lopez[1] , Pierre Duysinx[5]

[1] *Flanders Make, CodesignS corelab, Gaston Geenslaan 8, 3000 Leuven, Belgium*
[2] *Flanders Make, DMMS corelab, Celestijenenlaan 300, 3000 Leuven, Belgium*
[3] *KU Leuven, Department of Mechanical Engineering, Celestijenenlaan 300, 3000 Leuven, Belgium*
[4] *Code Product Solutions, Breinder 26, 6365CX Schinnen, The Netherlands*
[5] *University of Liege, A&M - Automotive Engineering, Allée de la Découverte 13A, 4000 Liege, Belgium*
[6] *Flanders Make, MotionS corelab, Gaston Geenslaan 8, 3000 Leuven, Belgium*

[*] *Corresponding author. Email: philip.eyckens@flandersmake.be*

As design changes in the production phase can be hundreds of times more costly than in the design phase, it is crucial to make sure that the designed product is actually manufacturable before start of production. To this aim nowadays often many manual iterations are needed between the designers and manufacturing experts, which leads to an inefficient design process and delayed time-to-market that in turn are detrimental for company competitiveness. Here we present the outline of a research effort to realize a substantially more integrated design process tailored towards both performance aspects and manufacturability. Key to this is the formalisation of Design for Manufacturing (DfM) rules within the functional CAD design stage. The traditional design approach is exemplified further in this work for the design of a gearbox housing for electric vehicle transmission systems. To realize substantial weight reduction without compromising performance, a novel multi-material design is proposed, constituting of both aluminium, to ensure structural integrity, and high performance polymer for additional structural integrity and leak-tightness under operating condition. Results shown include Topology Optimization (TO) under realistic loading conditions, scrutinizing material volume fraction boundary conditions and mesh sensitivity. Finally, some DfM rules and considerations in order to come to a manufacturable CAD design, are highlighted.

1. Manufacturing-informed Design and Optimization framework

Firstly, we present the main scope and first results of the Flanders Make ICON project ‘CAMEDO – Capitalizing Manufacturing Experience in Design and Optimization’. Its purpose is to develop and implement a generic and novel design approach that substantially reduces the time required to achieve a final manufacturable geometrical CAD design of a new mechanical component, by including and exploiting manufacturing information within the design process, both in late and early design phases. To ensure a continuous evaluation of the manufacturability of the component, Design for Manufacturing (DfM) rules are effectively integrated within the design process. Hereby three specific goals have been set, which are targeted within the project:

G1: establish a methodology to capture and formalize existing, heuristic manufacturing knowledge, in a structured database that can be exploited during the design phase of a new product.

G2: establish a prototype software tool able to assess the manufacturability of a mechanical component design based on a CAD file and accounting for the rules of G1.

G3: establish a methodology that embeds the manufacturing knowledge of G1 within a prototype topology optimisation tool, exploiting such rules in order to improve the manufacturability of the newly conceived designs.

A graphical abstract of CAMEDO is provided in Figure 1.

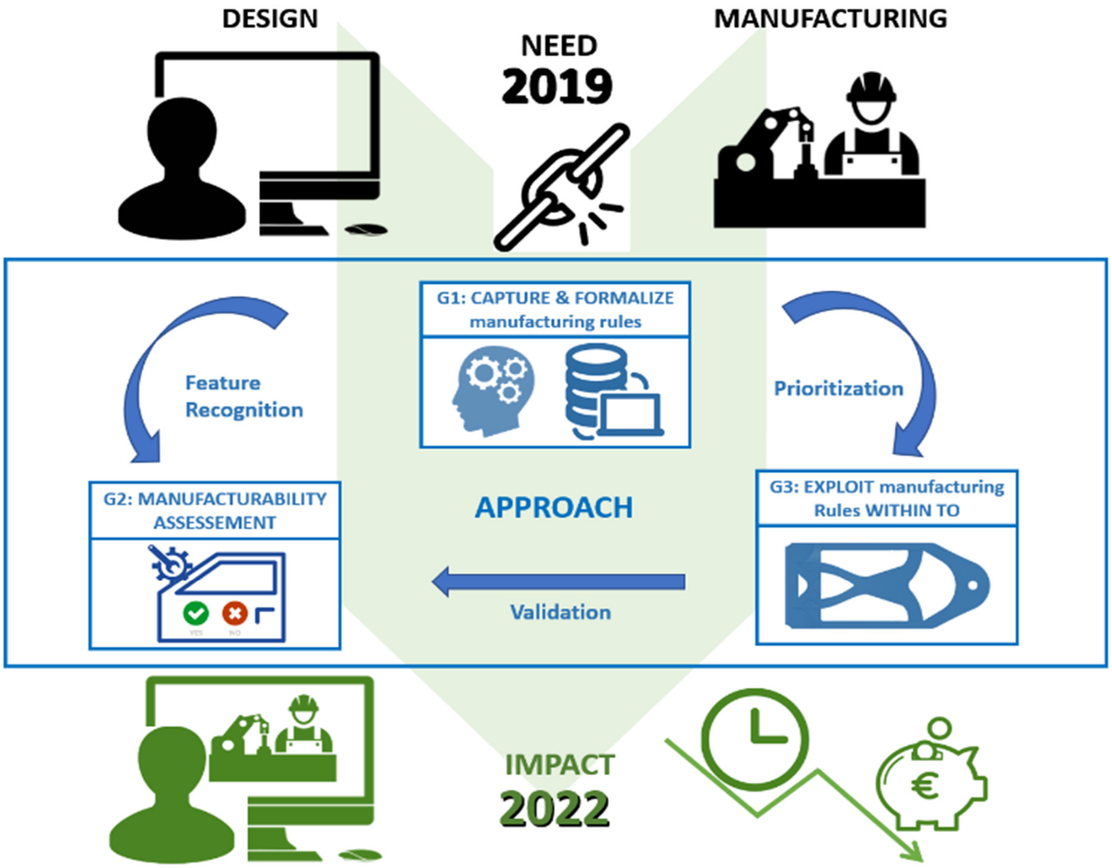

Figure 1: Flanders Make ICON project 'CAMEDO –
Capitalizing Manufacturing Experience in Design and Optimization'.

2. Multi-material gearbox housing for lightweight e-vehicle transmission systems

2.1 Use Case description

The use case studied is one of the four demonstrators developed in the Interreg project LightVehicle [1] and consists of a gearbox housing for Electric Vehicle (EV) applications. Traditionally, these components are manufactured fully in aluminium, but we aim to develop a novel multi-material design with two materials: aluminium and plastic (PA6 compounded with styrene maleic anhydride). Figure 2 shows the geometry of the component, as well as the loads applied on it. Two load cases are defined as below:

- Load Case 1: load applied in the smaller shaft hole (point 1), boundary constraints applied along the contour.
- Load Case 2: load applied in the larger shaft hole (point 2), boundary constraints applied along the contour.

The load values are provided by one of the participating companies and are kept confidential.

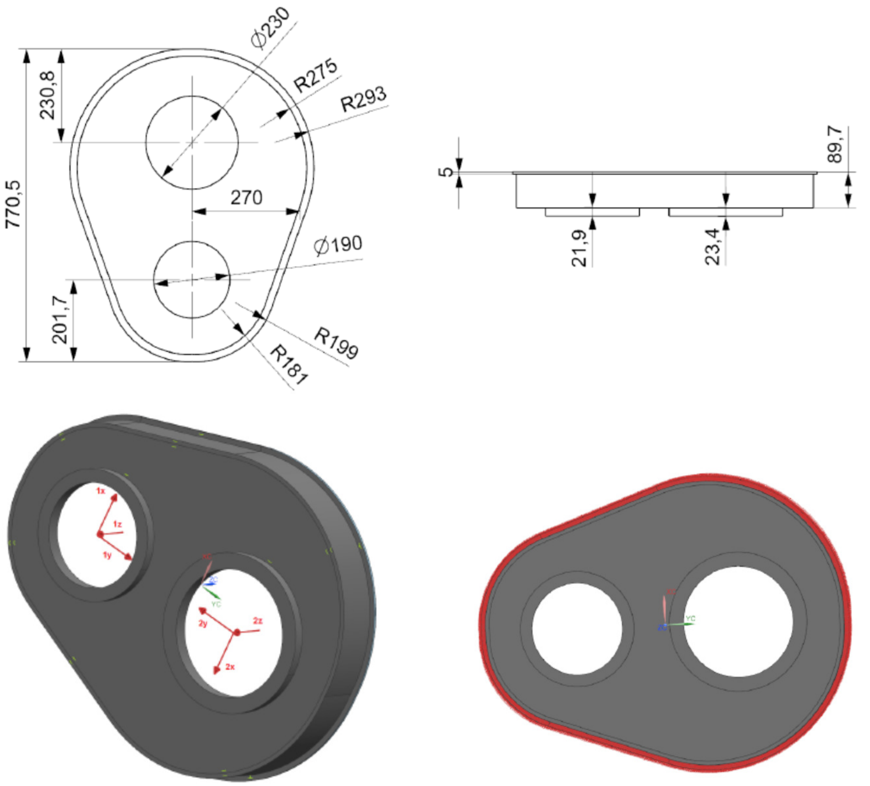

Figure 2: Multi-material gearbox design space and loadcases.

The goal is to maximize the performance of the gearbox housing while making sure that a certain weight reduction target is achieved. Therefore, the optimization problem proposed is defined as:

$$\begin{gathered} \min Compliance \\ \text{subject to:} \\ mass < 9\ kg \\ material\ fraction < P\ \% \end{gathered}$$

where *Compliance* refers to the strain energy and gives a measure of the structural stiffness (the lower the compliance, the higher the stiffness). We aim to study the influence of different plastic fraction constraints, as well as the influence of the mesh size.

2.2 Multi-material Topology Optimization

We start by solving the topological optimization problem described in Section 2.1 without imposing multi-material material fraction constraints. We employ the topology optimization tool [2], which is based on the method of moving asymptotes (MMA) [3]. The optimized result is shown in Figure 3. The yellow parts represent plastic material and the blue parts aluminium. We observe that nearly no plastic material appears in the final configuration, there is only some plastic at the boundaries between the aluminium and the void parts. In order to obtain a more realistic and manufacturable balance between the plastic and aluminium materials in the final gearbox layout, we introduce next a material fraction constraint.

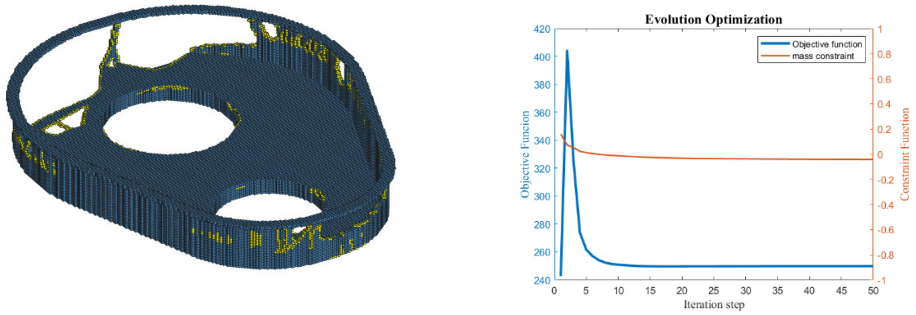

Figure 3: Topological optimization result of multi-material gearbox with mass constraint.

The material fraction constraint imposes a minimum percentage of plastic with respect to aluminium in the final layout. Figure 4 shows the layout of the gearbox after 100 optimization steps of the MMA algorithm for a material fraction constraint of respectively 40%, 50% and 60% of plastic. A consistent growth of the plastic islands can be observed for an increasing minimum fraction of plastic material. In order to maintain a sufficient stiffness – resulting from the minimization of the compliance – the central part of the gearbox housing in-between the shaft holes, is dominated by aluminium and also the vertical gearbox edges contain aluminium ribs as reinforcements.

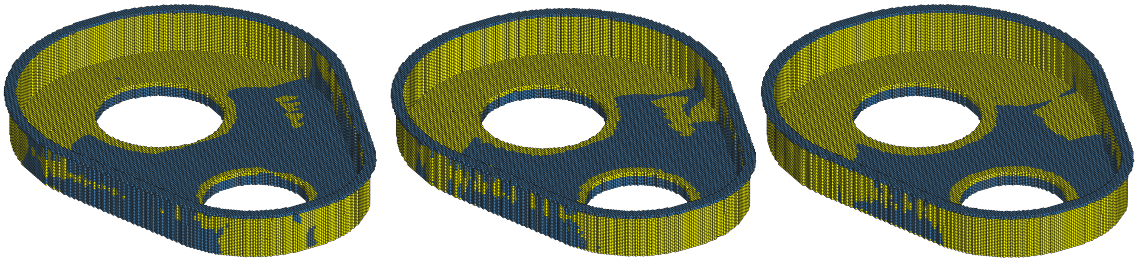

Figure 4: Final layout of the gearbox model for material fraction constraint of respectively 40%, 50% and 60% of plastic.

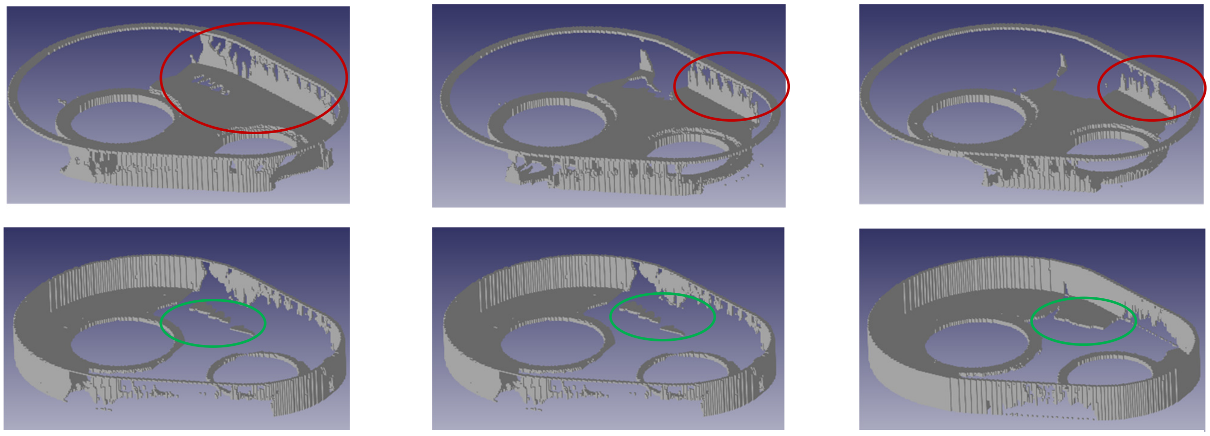

Figure 5: Aluminium (top) and plastic (bottom) fractions in the final gearbox layout for a minimum plastic fraction of respectively 40%, 50% and 60%.

By imposing a larger fraction of plastic material, these vertical aluminium ribs become more and more perforated which results in larger maximum compliance values, as can be seen in Table 1. The evolution of the aluminium/plastic ribs and the growth of the plastic islands is illustrated by the respectively the red and green circles in **Error! Reference source not found.**5, which shows the contributions of the 2 materials in the final layout separately.

The convergence of the optimization iterations is illustrated in Figure 6 and the final mass and compliance results are compared to the initial configuration in Table 1. As initial set-up, the entire gearbox layout is filled with aluminium material. In all optimization cases, the mass constraint of at most 9kg is satisfied and by imposing a larger plastic material fraction, a lower total mass is obtained, as expected from the lower mass density of the plastic material compared to the aluminium material. The convergence of the material fraction constraint becomes slower when imposing a larger fraction of plastic.

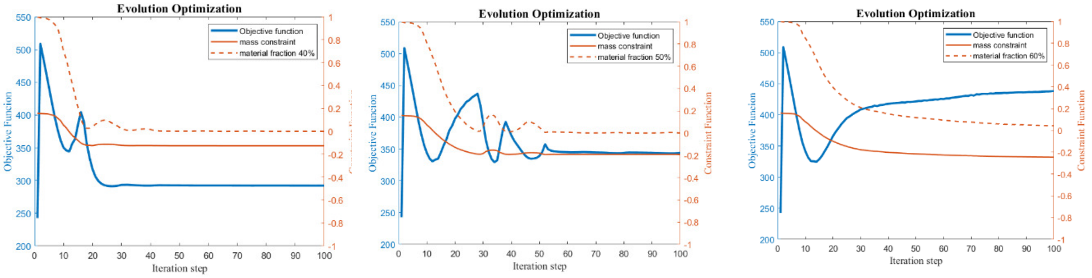

Figure 6: Optimization steps for a material fraction of respectively 40%, 50% and 60% of plastic.

	Initial set-up (full alum.)	Min. 40% plastic	Min. 50% plastic	Min. 60% plastic
Compliance	243	292	344	439
Mass	10.4	7.87	7.26	6.78
Max. displacement	0.41	0.47	0.54	0.69

Table 1: Optimized gearbox results compared to the initial configuration.

The above results consider a voxel based mesh with (160,240,36) voxels in the x-, y- and z-directions. From the gearbox dimensions of (608,771,110) mm, this corresponds to an element size of (3.8,3.1,3.1) mm. In order to illustrate the effect of mesh refinement on the topological optimization, Figure 7 shows the results for a (240,360,48) voxel mesh and a material fraction constraint of at least 50% plastic. This result is qualitatively and quantitatively very similar to the results from Figure 4 (central result with 50% plastic constraint), which illustrates the robustness of the optimization approach with respect to a larger set of design variables due to mesh refinement. We note however that for the refined mesh more iterations are required than for the coarser discretization in order to reach convergence. This complies with a general observation that for very fine meshes or very strict constraints – for example imposing a very low mass or an extreme material fraction constraint – the convergence of the optimization algorithm can become slower or can even be lost.

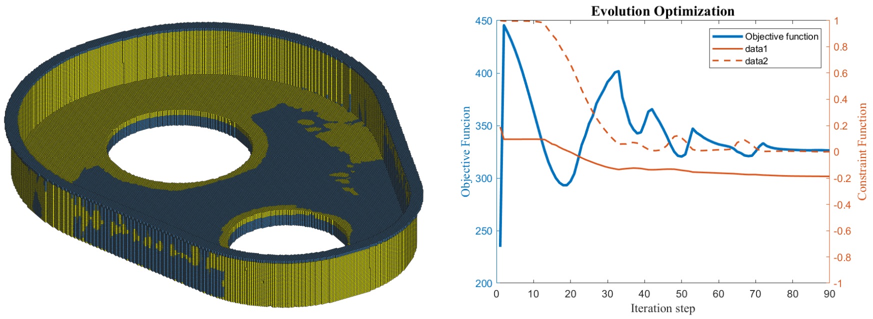

Figure 7: Final layout of the gearbox and optimization iterations for a 50% material fraction constraint and a finite element discretization using a (240,360,48) voxel mesh.

2.3 Translation to manufacturable CAD design

The obtained design that has been optimized for performance, is generally not or poorly manufacturable directly. In addition to this, different manufacturing methods, machines and materials impose very different requirements on the CAD design, and result in different properties, as illustrated in Table 2. Therefore, an iterative trial-and-error procedure traditionally needs to be adopted, involving manual iterations of CAD designs with accompanying manufacturing process simulation.

Production technology	Limitations	Batch Sizes	Tolerances*	Surface quality*	Costs
Milling	Almost no limitations design-wise, long processing times	Small volumes	Very precise	Very good	High costs
Casting	Difficult for thin wall thicknesses	Small to large volumes	Precise	Very good, if milled afterwards, otherwise moderate	Low costs in large series, secondary operations required
Metal injection moulding	Usually done for smaller parts in range of mm (tool cost, machine dimensions)	Small to large volumes	Very precise	Very good	High tooling costs (Assumption: most probably no price advantage towards current design)
Stamping	Not suitable for high and highly non-homogeneous wall thicknesses	Small to large volumes	Precise	Very good	Low costs in large series

Table 2: Manufacturing knowledge for different processes in scope for the multi-material gearbox.

Let's make this concrete for our use case. In a first design iteration the CAD engineer interprets the optimization results of section 2.1, resulting in the design shown in Figure 8. In this design, the "plastic islands" shown in Fig. 5 bottom row, are incorporated as 2 "bridges" of plastic between the 2 main plastic zones in the design, hereby realizing an additional design requirement, namely sufficient mechanical interlocking between the aluminium and plastic constituents. However, incorporating relatively thin bridges, as suggested by the Topology Optimization results, is in practice not manufacturable for the envisaged process, being injection (insert) moulding. This is due to excessive fill time (cf. right injection moulding simulation result in Fig. 8 with Moldflow [4]). Obviously, the bridges may be enlarged in the design for better manufacturability, but this has the risk of significantly deteriorating the performance, as the manufacturable CAD design "drifts away" from the performance-optimized TO design.

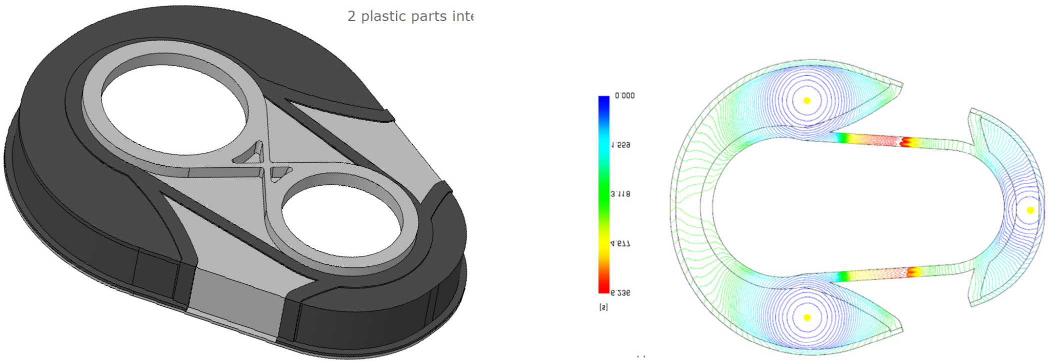

Figure 8: (left) CAD design with 2 plastic bridges providing mechanical interlock. It is however not manufacturable by injection insert moulding (simulation result on the right) due to excessive fill time causing weld lines and air traps.

In a next design iteration with modification to CAD and corresponding process simulation (Fig. 9), a compromise is found in removing the plastic bridges and incorporating smaller interlocks with geometries that are suitable for both the aluminium casting process and subsequent injection insert moulding process. Still, some compromises for manufacturability are required at the expense of performance. For instance, a single aluminium rib on either side of the gearbox wall is chosen, while for optimal performance in terms of weight and stiffness, Topology Optimization suggests multiple smaller aluminium ribs that are alternated by plastic, cf. Figure 5 top row.

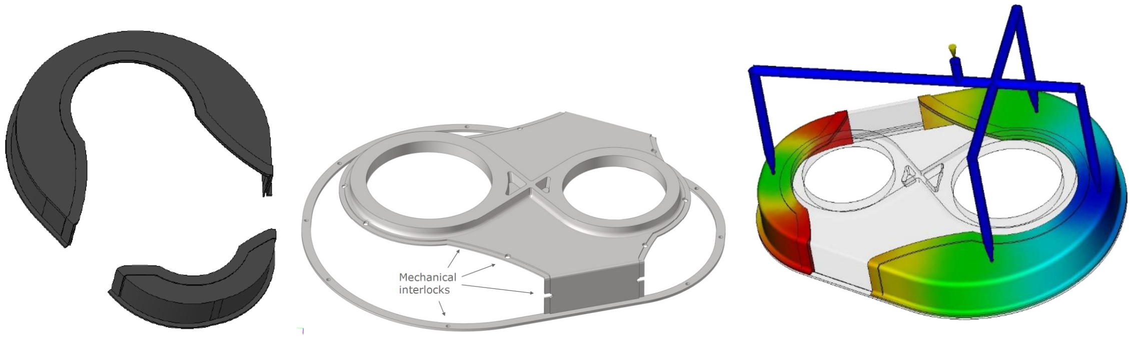

Figure 9: Next-iteration CAD design with 2 plastic parts (left) manufacturable by injection insert moulding (simulation result on the right). Additional details in the aluminium CAD (middle) provide mechanical interlocking between both materials.

3. Conclusions

This paper exemplifies a 2-stage design approach of firstly adopting topology optimization for performance optimization, followed by iteratively deducting manufacturable CAD designs that are simulated for one or more candidate manufacturing processes, possibly in conjunction with performance validation simulations.

The presented results demonstrate how by combining topological optimization with multi-material constraints the design of a gearbox can be substantially improved, realizing more than 30% weight reduction. To come to a manufacturable design however, post-processing of the optimal design, common state-of-the-art practise, means making concessions to the optimally performing solution, at the expense of additional effort in the design process.

As outlook, the CAMEDO project (Capitalizing Manufacturing Experience in Design and Optimization), shortly outlined in this work, will investigate how manufacturing design guidelines may be translated to Design for Manufacturing (DfM) rules that can be exploited as constraints in

Topology Optimization. Additionally, the envisaged Formalization Toolbox of DfM rules may be equally exploited to evaluate existing CAD designs for specific processes, machines and material choices. This will improve the overall design process significantly in terms of required resources and robustness.

4. Acknowledgements

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