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## Influence of manufacturing constraints on the topology optimization of an automotive dashboard

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### Abstract

Topology Optimization (TO) methods optimize material layout to design light-weight and high-performance products. However, TO methods, applied for components or assembly with high complexity shape or for structures with copious number of parts respectively, do not usually take into account the manufacturability of the optimized geometries, then a heavy further work is required to engineer the product, risking to compromise the mass reduction achieved. Within an Industry 4.0 approach, we propose to evaluate manufacturing constraints since early stages of the conceptual design to perform a TO coherent with the manufacturing technology chosen. Several approaches of TO with different manufacturing constraints such as casting and extrusion are proposed and each solution is compared. The optimum conceptual design is determined in order to minimize the component weight while satisfying both the structural targets and the manufacturing constraints; a case study on a high-performance sport car dashboard is finally presented.

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## 1. Introduction

It is widely recognized that the weight reduction for car manufacturers is a great way to fulfill the reduction of emissions and fuel consumption, and finally, to contain the design and the manufacturing cost [1, 2]. The Finite Element (FE) models and the Topology Optimization (TO) as well, are crucial tools for industrial purposes, and especially for aerospace and automotive applications; in fact, their capability to mimic and to achieve structural targets such as stiffness, stresses and dynamic behaviour have been applied to prevent failure [3-5]. In particular, TO may provide useful guidelines for the design of mechanical components for structural applications. Nevertheless, the result of TO is not easy to interpret and even worse it does not fit well with the manufacturability of the components [6].

In the present paper, a topology optimization design methodology is presented and applied to an automotive sport car dashboard. Both structural targets and manufacturing constraints have been considered. Manufacturing constraints have been applied in the early stage of the optimization analysis, in order to obtain compatible results for manufacturing process and to avoid the non-accepted results for an engineering point of view.

In fact, topology optimization aims to find the optimum structural mass distribution in a domain. The theory of topology optimization is laid down in the work of Bendsøe and Sigmund [7]. Cavazzuti and al. [8] studied different optimizations for a full automotive car chassis. It is important to point out that topology structural solutions are mesh-dependent, as mentioned in [9-10], and the use of proper filters could simplify the redesign process [11].

For automotive components, the classic trial and error design procedure is becoming inadequate. Cavazzuti in [12-13] and Torricelli [14] applied the topology optimization to the chassis of a sport car in view of weight reduction, a comparison between spider and coupé architecture has been discussed. The literature evidence a lack of specific studies for TO that considers manufacturing constraints in complex structures, in fact, in the previous works [12-14], the manufacturing constraints have been neglected during the optimization process. The manufacturing requirements have been included at the “Computer-aided design (CAD) re-interpretation ... executed next to ... the topology optimization results” as mentioned in [18] and also in Cavazzuti [8].

Instead, many works investigated the influence of the manufacturing constraints into the TO process for mechanical components with simple geometry *e.g.* cantilever beam with point load. Bracket et al. [16] and Leary [17] proposed an overview of the issues and the opportunities in the TO to Additive Manufacturing. In 2016, Vatanabe et al. [18] illustrated the manufacturing constraints technique based on unified projection-based approached for a wide scenario of manufacturing processes *e.g.* extrusion, casting, forging, ... . Chen [19] presented the topology optimization for manufacturability associated with visibility map approach. Two testcases have been presented: the first one treated the manufacturability of a component by 3-axis CNC machining (TO with unidirectional manufacturing constraint); the latter one considered a component manufactured by casting (TO with bidirectional manufacturing constraints).

In the present paper, a design of an aluminium sport car dashboard is developed in view of weight reduction with torsional and bending stiffness targets. This study is manufacturing oriented and aims to find the optimal solution that is included into the TO space reduced by the manufacturing constraints. Both the casting and the extrusion process are investigated. The article is organized as follows. In the first phase, a TO of the dashboard neglecting manufacturing constraints is evaluated. Subsequently, topology optimizations with single and split draw constraints is performed to mimic the casting technology process. Afterwards, the trends of the optimal TO solution for established mass fraction is discussed in order to find the threshold of the maximum stiffness and minimum weight, which is the possible gain in performance. In the third section of the paper, TO analyses have been performed considering the extrusion manufacturing aspects. Finally, a comparison between the TO results considering casting and extrusion technological aspects is discussed.

## 2. Methods of topology optimization

A structural optimization problem aims to find a local minimum:

$$\begin{aligned} & \underset{\mathbf{x} \in D}{\text{minimize}} f(\mathbf{x}) \\ & \text{subject to } c(\mathbf{x}) \geq 0 \end{aligned} \quad (1)$$

where the vector  $\mathbf{x}$  represents a suitable parameterization of the problem,  $D$  is the design/volume space,  $f(\mathbf{x})$  is the objective function, and  $c(\mathbf{x})$  are the constraints of the optimization. The objective function and the constraint functions are structural responses obtained from a FE analysis. The selection of design variables is influenced by the optimization technique under scrutiny such as topology, topometry and size optimization.

The theoretical basis of the optimization method is extensively described in [7, 20]. In particular, for topology optimization, the main scope of the method is to find the optimum material distribution in a structure. Finite Element analyses are performed assuming as parameters vector  $\mathbf{x}$  the element-by-element relative material density which is allowed to vary with continuity:

$$\mathbf{x} = \{x_i \in (0,1], \forall i = 1, \dots, N\} \quad (2)$$

where  $N$  is the number of finite elements in the structure.

The density  $\rho$  of the  $i$ -th element is given by:

$$\rho_i(x_i) = x_i \rho^* \quad (3)$$

where  $\rho^*$  is the full density of the material. Therefore, the material density and the material stiffness are correlated.

The Solid Isotropic Material with Penalization (SIMP) method, which is adopted in this paper, assumes that the stiffness  $E$  of the  $i$ -th element is given by

$$E_i(x_i) = x_i^p E^* \quad (4)$$

Where  $E^*$  is the full stiffness of the isotropic material and  $p$  is the penalty factor, see [7,8]. The topology optimization algorithm alters the material distribution to optimize the objective under given manufacturing or machining constraints [6, Fig. 2]. In the casting process, cavities that are not open and lined up with the sliding direction of the die are not feasible. Designs obtained by TO often contain cavities that are not viable for casting. The transformation of TO result into a feasible component could be extremely difficult, if not impossible. In some cases, where this transformation is made, the likelihood of severely affecting the design optimum becomes relevant. In the following, topology models based on draw direction constraints and on die to slide in a given direction are presented.

Zuo et al. [6] have proposed an analytical formulation to introduce the manufacturing constraints into the optimization process. The draw constraint may be expressed with the following formula:

$$\sum_{k=1}^{K1-1} |(x_{ij}^e)_{k+1} - (x_{ij}^e)_k|_p \leq \delta; \quad i = 1, \dots, n_x; \quad j = 1, \dots, n_y \quad (5)$$

where:

- $(x_{ij}^e)_k$  is the density of the  $k$ -th element placed in  $(i,j)$  on the projection plane  $p$ ;
- $K1$  is the number of elements lying at  $(i,j)$ ;
- $n_x$  and  $n_y$  are the numbers of elements in the  $x$ - and  $y$ -direction respectively lying in the projection plane  $p$ ;
- $\delta$  is a small positive quantity.

To have a result which is suitable for the casting technology process, the draw direction is defined.

In addition, the constraint for symmetrical design of the component can be expressed as follows:

$$\sum_{k=1}^{K2} |(x_{ij}^e)_k - (x_{ij}^e)_{-k}|_M \leq \delta; \quad i = 1, \dots, n_x; \quad j = 1, \dots, n_y \quad (5)$$

where:

- $(x_{ij}^e)_{-k}$  is the density of the symmetric element of  $(x_{ij}^e)_k$  respect to the plane  $M$ , that represents the  $xy$  plane.
- $K2$  represents the number of elements placed in  $(i,j)$ .

The previous formulations have been implemented into the present paper for the topology optimization of the dashboard.

### 3. Topology optimization for an automotive dashboard.

In the present paper, a gradient based optimization algorithm has been implemented, in particular the Method of Feasible Directions. The approach of *Adjoint Variable method* [21] has been considered for the analysis in order to reduce computational costs; this approach allows a single forward-backward substitution for each design variable.

On the design variables, *Move Limits Adjustments* have been applied to preserve the accuracy of the TO results. Small move limits lead to smoother convergence instead large move limits may lead to oscillations between feasible and infeasible designs. In this activity, the move limits of 20 per cent of the current design variable values have been used as compromise between accuracy and computational time.

At each iteration of the optimization process, the objective function and the all constraints of the design problem are evaluated. Retaining all of these responses in the optimization problem causes two disadvantages: it can result in a big optimization problem with a large number of responses and design variables; the design sensitivities of these responses need to be calculated. Hereinafter, in addition, a *Constraint Screening* has been implemented. In this manner, the number of responses in the optimization problem is trimmed to a representative set. This method adopts the fact that, in a given number of constrained responses, the constrained responses of the same type that are less critical will not affect the direction of the optimization problem. Therefore, they can be removed from the problem for the current design iteration. During the present activity, twenty most critical constraints only that come within fifty per cent of their bound value for each response type have been considered.

The software package employed for the dashboard optimization is Altair OptiStruct 13. Figure 1.a shows the global view of full vehicle and the dashboard design space considered for the TO under scrutiny. Figure 1.b displays the detailed view of the dashboard admissible design space. The model consists of over 600'000 tetrahedral 4-nodes elements having 8 mm average mesh size.

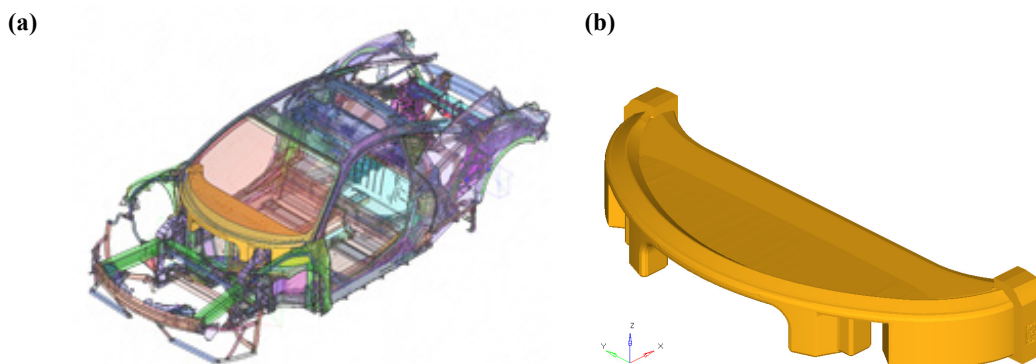


Fig. 1: (a) the chassis under scrutiny, (b) the dashboard design space.

In the following, the purely bending and the purely torsional loading conditions have been considered for the dashboard optimization; in Figure 2 the loading configurations have been exemplified.

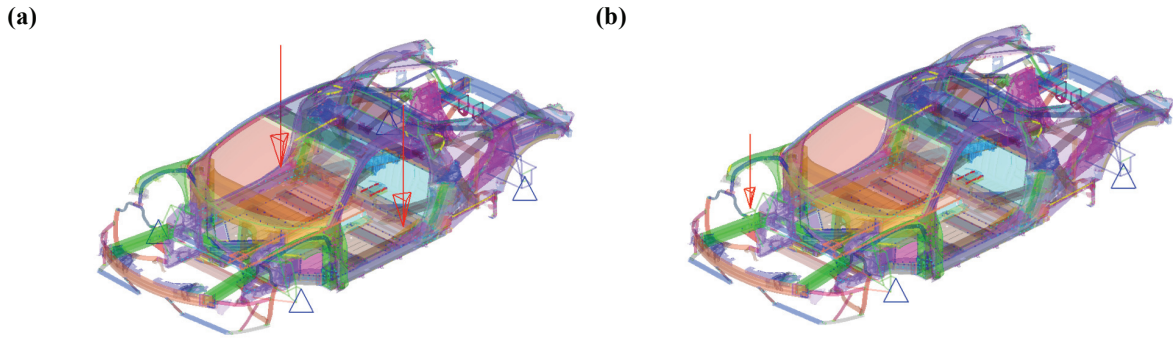


Fig. 2. Bending (a) and torsion (b) load conditions.

A standard aluminum alloy had been employed for the new dashboard and the TO has been performed considering the constraints related to casting and extrusion manufacturing technologies. In addition, a symmetry design constraint has also been introduced into the TO methodology: the symmetry plane is located in the mid-side of the vehicle, and the plane is normal to the  $y$ -direction.

The material of the dashboard is assumed to behave elastically and the Young modulus and the Poisson's ratio are equal to 70000 MPa and 0.3, the material density is equal to  $2.7 \text{ kg/dm}^3$ . This component represents the 7.2 per cent of the overall weight of the vehicle Body-In-White (BIW).

### 3.1 TO with weighted compliance for each loading condition without manufacturing constraints.

The objective of the TO is the reduction of the weighted compliance for each loading condition. The compliance is defined as a magnitude inversely proportional to the stiffness, whereby maximize the stiffness is equivalent to minimize the compliance. Two loadcases were considered: torsion and bending.

In the torsional load case, the displacement of four nodes were monitored (one for each shock-towers in proximity of the vehicle floor). In the bending load case, six nodes were monitored: the same four nodes considered for the previous torsional loadcase and two additional nodes located at the bottom surface of the sills.

The displacements of these reference nodes have been constrained to improve the actual stiffness of the component. It was constrained also the maximum proportion of the mass of the component adoptable by the solver to achieve the solution, in order to obtain a design that fulfills the desired stiffness and that weights a given percentage of the overall mass of the component described by the design space. This percentage varies from the twenty to the eighty per cent. A minimum dimension of the sub-structures that the TO generates has been imposed equal to 20 mm.

For brevity, the topology results will be restricted to the model with constrained mass at twenty and at the eighty per cent of the overall mass of the dashboard described by the design space, see Figure 3.a and Figure 3.b respectively. The results clearly show that the structure obtained, even in the case of more restrictive constraining (Figure 3.a) is difficult to interpret and to realize.

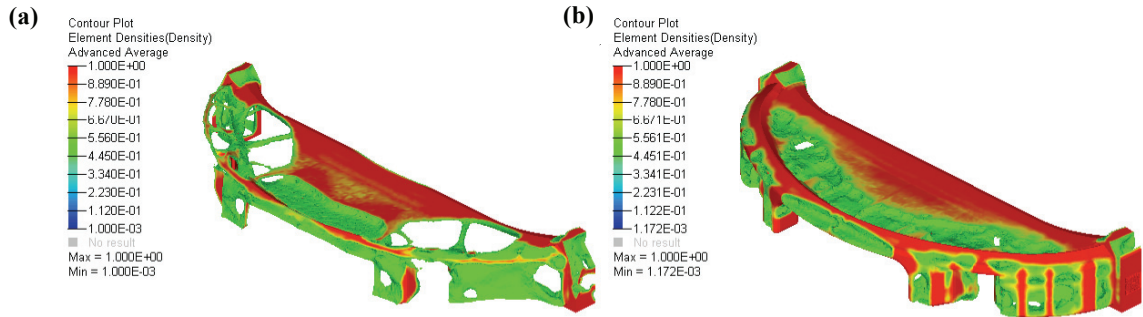


Fig. 3. Topology results with constrained mass at: (a) 20 per cent and (b) 80 per cent.

3.2 TO considering casting manufacturing constraints.

A second round of TO has been performed, the objective of the TO remains the reduction of the weighted compliance for each loading condition including also two types of manufacturing constraints for the casting process: the first model considers one draw direction along the  $z$ -axis alone, instead, the second model considers two draw directions along  $z$ -axis, Figure 1.b. Which means that the topology will return a more feasible dashboard achievable through a die along  $z$ -positive direction (single draw), and both along  $z$ -positive and negative directions (double draw). Draw angles have not been constrained. The symmetry plane normal to the  $y$ -direction and the minimum dimension have been defined as previously mentioned.

Figures 4-6 show the topology results of the models with constrained mass at twenty and the eighty per cent in the case of single and double draw manufacturing constraints, respectively. Figure 4.a shows a dashboard defined by framework that is well feasible through a casting process and where the mass reduction has been maximized and the global stiffness has been achieved.

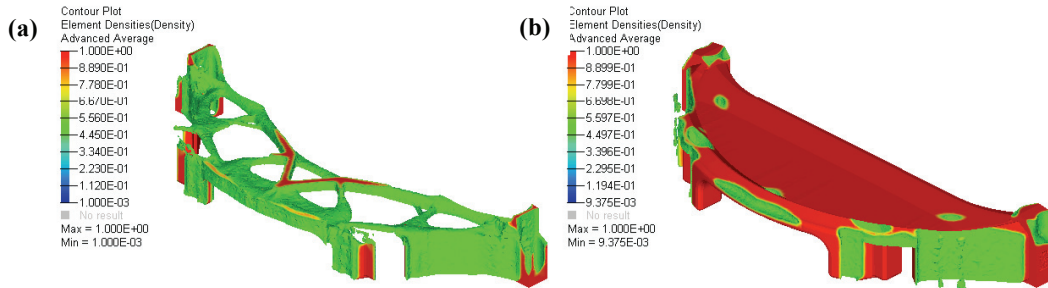


Fig. 4. Topology results with constrained mass 20% (a) and 80% (b) considering single draw constraints.

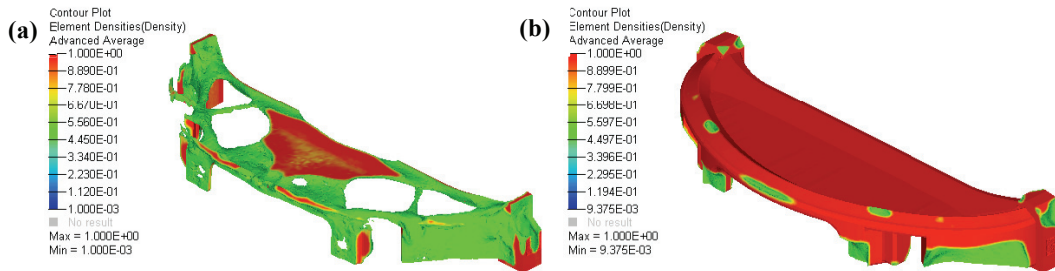


Fig. 5. Topology results with constrained mass 20% (a) and 80% (b) considering double draw constraints.

It is observed that only the topology model with double draw constraints removed the material along  $z$ -negative direction, as shown in Figure 6.a, instead the TO with the single draw constraint did not remove material along  $z$ -negative direction. Because of the different manufacturing constraint, the structures of the two TO results are substantially different. In the first case the results is well defined and a framework structure is evidenced.

At the four connections (2 lateral and 2 frontal joints) between the component and the automotive chassis, a significant material distribution is requested in both cases (Fig. 6.a, b).

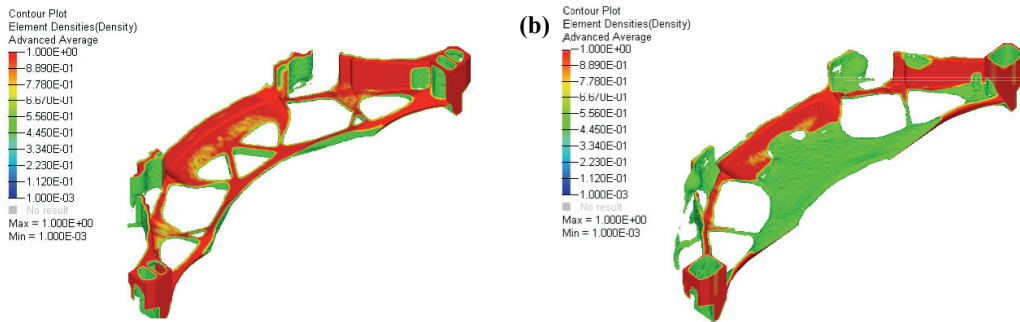


Fig. 6. Bottom view of topology results with constrained mass 20%: (a) considering single or (b) double draw constraints.

### 3.2.1 Trends of the optimal TO solution for established mass fraction.

In order to compare the influence of the manufacturing constraints on the compliance of the dashboard, 21 models have been performed varying the admissible mass fraction ( $M$ ) of the dashboard design space. The mass fraction is comprised between the interval 0.2-0.8, this variable is reported in Figure 7 at the  $x$ -axis. The value of the minimum compliance (therefore maximum stiffness) computed for each model is reported along the  $y$ -axis normalized to the maximum value extracted from the 21 forecasts.

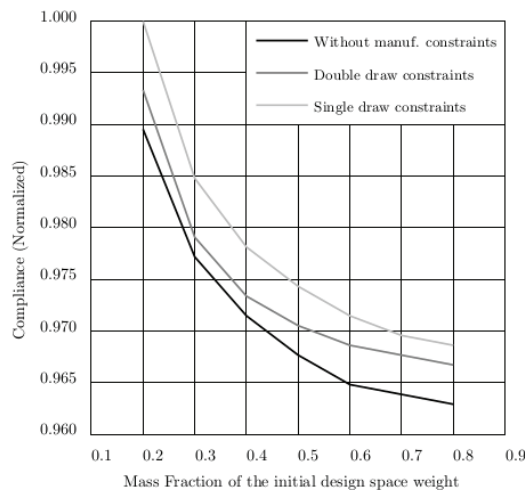


Fig. 7. The comparison of the optimal TO solution at imposed mass fraction considering or neglecting the manufacturing constraints.

Figure 7 includes the FE results: the black, the dark-gray and the light-gray curves represent the TO results without considering manufacturing constraints, nor including the single draw constraints or the double draw constraints, respectively. It is observed that for a given mass fraction, the normalized compliance of the TO without

manufacturing constraints is the lowest, so it is the stiffest solution. The normalized compliance with single constraints, instead, for the same given mass fraction is the highest, so it represents the less stiffener solution. However, the results of the TO without considering manufacturing constraints might be strongly manually re-interpreted from the designer leaving partially the reduction of weight and the stiffness performance.

### 3.3 TO with extrusion manufacturing constraints.

The methodology presented in the previous paragraphs might be implemented considering the manufacturing constraints that characterize the extrusion manufacturing process. The wall thickness of the extruded parts has not been constrained and the requirement of a symmetric design has been maintained. The dashboard design domain (Figure 8.a) has been divided in four subdomains differing for four extrusion directions. This non-conventional design strategy has been driven by the TO results extracted considering the casting manufacturing constraints. In fact, Figure 4.a suggests a similar wireframe structure. The results of Figure 8.b shows that the rear beam contributes significantly to the overall stiffness of the structure as mentioned in the previous paragraph, in fact this beam requires the highest material distribution if referred to the further sub-components/sub-domains. The TO results show a structure difficult to interpret with discontinuous and hollowed area. The compliance of the TO forecast considering the extrusion manufacturing constraints is enhanced of 0.026 compared to the compliance of the TO forecast obtained considering the single draw manufacturing constrained at the 20 per cent of the mass fraction of the initial design space weight. An improvement of the manufacturing conditions setup *e.g.* minimum and/or customized thickness of the extruded sub-domain is required, therefore a further FE forecast should be assessed. This topic is deferred to a future paper.

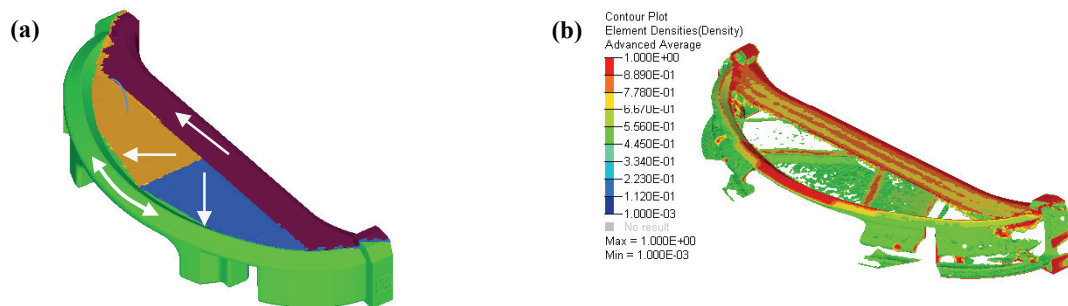


Fig. 8. (a) the four design domain and (b) the results obtained for the TO that considers the extrusion manufacturing constraints.

## 4. Conclusions

The manufacturing constraints strongly influence the design process of a component, its final shape, mass and compliance (or stiffness). The integration of the manufacturing constraints into the topology optimization has been presented for a complex component like an automotive dashboard for casting or extrusion manufacturing process. Torsion and bending loadcase conditions were considered in the TO in order to minimize the weight of the component, and to improve the stiffness of the actual component. The TO results neglecting the manufacturing constraints show a final discontinuous and unfeasible structure that achieve the maximum reduction of weight. The results obtained considering the limitations due to casting process illustrates a well-defined component with a significant reduction of the mass if referred to the actual aluminum model. The TO results obtained for and extrusion process point-of-view evidence a structure difficult to manufactured, therefore a further and detailed assessment of the extrusion manufacturing process should be performed in a future paper.



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