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STUDY OF TOPOLOGY OPTIMIZATION PARAMETERS AND SCAFFOLD STRUCTURES IN ADDITIVE MANUFACTURING

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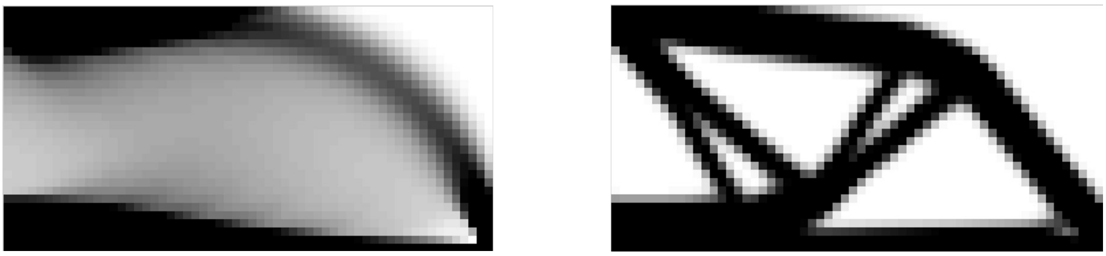
Abstract. *This work falls within the scope of topology optimization procedures and additive manufacturing technologies. In recent years the topology optimization has become a perfect tool to maximize the potential and freedom that these revolutionary manufacturing technologies offer, allowing to conceive designs that utilize available resources optimally. However, there are still many theoretical and practical issues regarding automatic integration of both technologies. This investigation aims to advance in this line of research, where algorithms that provide the ability to control and minimize support structures will be developed. These scaffold structures are usually necessary when additive manufacturing is used to construct the geometries obtained after the optimization process. The algorithms to be implemented in this project would offer the possibility to control the formation of scaffold structure and minimize them when necessary. For this purpose, this introductory paper discusses the effect of different parameters and restrictions that may have an influence on the formation of scaffold structures and are eventually involved in the topology optimization process. Considered parameters include the filter radius applied for mesh independency, penalization factor in the SIMP power law and the perimeter constrain. These strategies are frequently used to assure existence of solutions and mesh independent 0-1 designs, when a high degree of complexity is usually undesired for traditional manufacturing. This paper discusses the effect of these parameters on the length and inclination of members present in the optimum topologies. The requirement for several Additive Manufacturing processes to use support structures for large overhangs provides justification for investigating additional and specific methods for including this measure into the optimization process. In this line of work the authors will also propose a new approach to evaluate the global angle and overhang of a topology with intermediate densities, which can be incorporated as a manufacturing constraint into the topology optimization process in order to explicitly specify the amount of support structures desired in the final solution.*

1. INTRODUCTION

In past years, and due to factors such as limitations on accessible manufacturing technologies, difficulty for interpreting results,… topology optimization has not been used beyond theoretical arguments, and it was when techniques like penalization methods (SIMP, …), mesh independent filter… were developed that topology optimization began to sprout on the industry.

The tendency back then, due to the limitations that manufacturing technologies seemed to have at that time, was to simplified the optimum design using penalizations methods, filters, … Hence, despite of being close, the resulting geometry wasn´t the optimal.



(a) (b)

Figure 1: Differences between a Real Optimum (a) and a Simplified Optimum (b)

The complexity of the structure used to be a problem and many authors worked on analysing it by using filter and different parameters [1]

Now the situation is quite the opposite. The introduction of the modern additive manufacturing technologies has enforced the usage of topology optimization in the design process, as combining both one can fully exploit the capabilities of each of them. However, that combination presents a critic point as although the comparatively lack of limitations, additive manufacturing technologies posses one weak point which is commonly known as the overhang problem. This means that during the manufacturing process curling/warping may appear due to high temperature gradients. These situations are conditioned by the angel (relative to the structure's growing direction) of inclination of the member and its length (perpendicular projection to the structure's growing direction).

In order to face these problems, but never to avoid them, what it's been commonly done is to introduce scaffold structures. Nevertheless, the introduction of these structures supposes an increment of needed initial raw material and hence an increment of economic cost as well as an increment on manufacturing time (there are needed some processes to put and remove them), contamination… The current tendency then is to develop methods that are able to avoid these structures. These methods should include the overhang constraint into the topology optimization process.

Anyway, some authors [2] have already mentioned that increasing the complexity of the structure may help obtaining scaffold structure free geometries as the more complex a geometry is, more and shorter members are created and they can have a similar behavior to scaffold structures. Consequently, if the complexity of the structure can be controlled by controlling the typical parameters of the topology optimization problem, it may help reducing the amount of scaffold structures and may make more affordable the additive manufacturing process.

As it is been already mentioned, the overhang problem is conditioned by the length and inclination of the member and by increasing the complexity of the structure we are directly controlling one of these parameters, the length, and as will be explained later on, minor length equals a minor problem. An example of the mentioned is shown in figure 2.

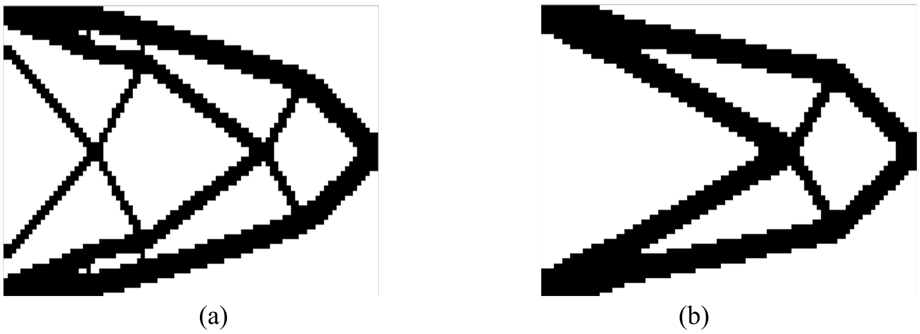


Figure 2: Differences between a complex geometry (a) and simpler geometry (b) for the same structural problem

While image 2(a) shows an structure with a good amount of thin and short elements with appropriate inclination (respect to a vertical growing direction) to be manufacture by additive methods with probably no scaffold structures, image 2(b) shows a simpler geometry where members' inclination will be problematic and hence scaffold structures would be needed.

This paper seeks to present the effects of the typical topology optimization problem parameters over the complexity of the geometry and it will be proposed a technique with which the probability/necessity of an structure for needing scaffold structures can be calculated.

2. PROPERTIES OF A MEMBER

Before going in any farther detail, the properties of structural members are presented.

2.1. Inclination, Ω.

The inclination is a critical factor in the fulfillment of the overhang constraint, but it does not influence directly on the complexity of the global geometry. The inclination is measured always respect to the structural growing direction. This is represented by the vector **r**. The inclination is a relative angle and is named Ω.

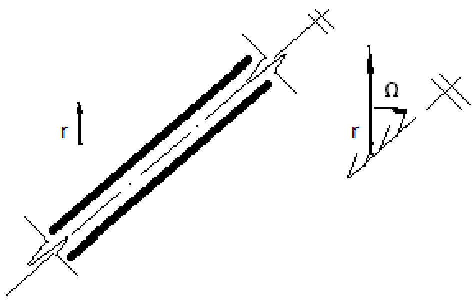


Figure 3: Inclination of a member

Regarding the restriction, problems begin to appear for relative angles greater than 45º, which is considered the theoretical limiting angle, but some authors [2] propose a penalization for the combination of the inclination and the length of the member, considering the combined effect critical for the fulfillment of the constraint. This gives an idea of the important effect that complexity casts over the problem.

2.2. Length, δ.

The length, δ, is relevant in the fulfillment of the constraint and it influences directly on the complexity of the structure. Low values of δ suppose greater amount of members, therefore a structure with more and thinner members which ends being a more complex structure.

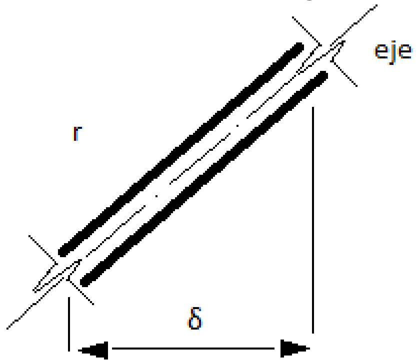


Figure 4: Length of a member

This parameter, δ, also affects the thickness of the members (high value of δ = high value of d).

2.3. Thickness, d.

The thickness, d, does not influence the complexity non the constraint, as the constraint is not mechanic but thermal.

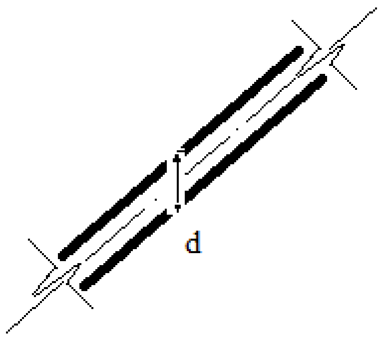
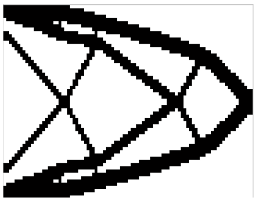
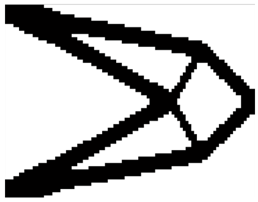


Figure 5: Thickness of a member

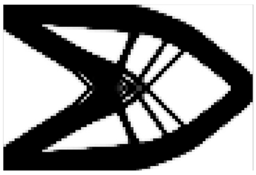
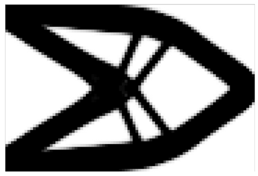
3. EFFECTS OF THE OPTIMIZATION PARAMETERS

In this section there are going to be shown the effects of the typical parameters of the topology optimization over the complexity of the final geometry. Considered parameters include the filter radius applied for mesh independency, objective volume and the perimeter constraint.

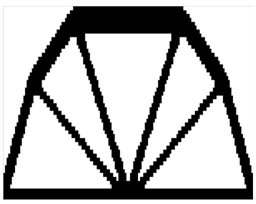
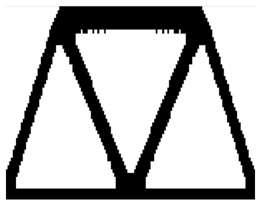
For filters, since their introduction, they have always been used to avoid the generation of checkerboard-like problems due to the introduction of penalization processes such as the SIMP method. Filters tend to concentrate material where a predisposition for this exists, but always inside a region controlled by the value of the filter radius, rmin. However, concentrating material means to simplify the geometry, so the bigger the filtering radius is the simpler the geometry will became. Figure 6 shows this effect.

(a1) (a2)

(b1) (b2)

(c1) (c2)

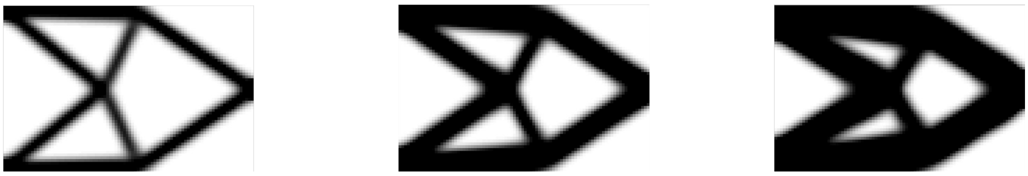
Figure 6: Effect of the filter radius on geometry's complexity. **(a)** Discrete variables. 90x60 elements. V*=0.3, (a1) rmin=1.5, (a2) rmin=2.5. **(b)** Continuous variables. 90x60 elements. V*=0.5, (b1) rmin=1.05 and (b2) rmin=1.25. **(c)** Discrete variables. 150x50 elements. V*=0.3, (c1) rmin=1.5, (c2) rmin=3.5.

Figures (a1), (a2), (b1) and (b2) show the effects of varying the values of the filter radius on a typical cantilever beam optimization problem, for discrete and continuum variables respectively. For both cases the lower value of the filter results in a more complex geometry. From figures (a1) and (a2) in can be appreciated, as it was explained before, that the more complex geometry is more suitable (for a vertical growing direction).

In the other hand, figures (c1) and (c2), although for lower filter radius the geometry is more complex, it is not more suitable (for a vertical growing direction) as some members' relative inclination is greater than the theoretical limit of 45º.

As it can be extracted from this examples there is a clear effect of the filter radius on the final complexity of the structure, but there cannot be established a concrete pattern that could be applied on any geometry and problem. In general terms, low values of the filter radius result in more and thinner members, increasing then the complexity of the geometry but not always resulting in a more suitable geometry for additive manufacturing.

The to be accomplished volume also has a direct effect on the member inclination. The need for occupying the same space with more material supposes, in general, that the inclination of the members will vary due to the increase of member thickness. Figure 7 shows this effect.

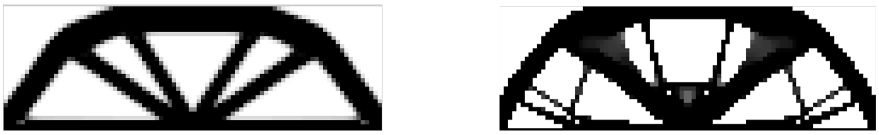


(a) (b) (c)

Figure 7: Effect of the objective volume on the member inclination. Continum variables. 90x60 elements .(a) V*=0.3, (b) V*=0.5, (c) V*=0.65. Rmin=3.5.

From (a) to (c), it can be appreciated how member inclination changes as objective volume increases. Inclination of the boundary elements is what really matters, and it is seen that the greater the final perimeter is, que greater the inclination it is.

In the case of the perimeter, its control is one of the proposed methods for controlling de complexity of the structures. This method was proposed by [3] and its initial objective was to substitute the filtering processes and to reduce/control the complexity of the final geometry. In order to do so, an upper bound was written for the perimeter, reducing this way the number of members and holes. In the the contrary is made and a lower bound is written so that a great amount of members are obtained increasing like that the final complexity of the geometry.



(a) (b)

Figure 8: Effect of the objective perimeter. Continum variables. 90x30 elements .V*=0.5, rmin=1.2. (a) P=626, (b) P=800.

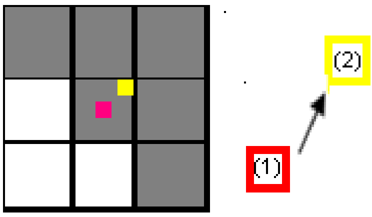
In figure 8 it can be appreciated the optimum structure (a) and the optimum structure with a greater perimeter constraint (b). It is easily seen the increase of the complexity of the geometry when increasing the perimeter, and this happens because the perimeter is the longitudinal measure of every structural boundary, therefore increasing the perimeter increases the amount of holes and members of the final geometry. That way, members that will work as natural scaffold structures can be created avoiding thermal problems and also external scaffold structures.

It can be appreciated how every of the parameters has its own effects on the complexity of a geometry, and hence, on the suitability of the structure to be manufactured by additive manufacturing technologies. Besides, the parameters are connected among them as one affects the other (i.e: the greater the objective volume is, the greater could the perimeter become and more members could be created).

4. THE PROPABILITY FOR THAT A STRUCTURE NEEDS SCAFFOLD STRUCTURES, Ω.

Now that the effect of the different parameters over the complexity of a geometry is been explained, a method for obtaining the probability for that a structure needs scaffold structures is presented, regardless the value of the different parameters. The method presented in this paper is based on discrete variables, but the aim is to develop an universal method.

The objective is to find a number that can describe in which amount the overhang constraint is violated, or what is the same, the probability for that scaffold structures are needed. The process starts calculating variable gradients for 3x3 mask placed with center on the center of every element. These gradients will be calculated in the vector **vcg**, where **vcg** is the direction vector from the geometric center of the mask to its center of gravity. This method is known as SUSAN (Smallest Univalue Segment Assimilating Nucleus) and was developed as a method for locating boundaries [4, 5].



vcg=(xcg,ycg)

$$xcg = \frac{\sum_{i=1}^{n} xi \cdot \rho i}{\sum_{i=1}^{n} \rho i} \qquad (1)$$

$$ycg = \frac{\sum_{i=1}^{n} yi \cdot \rho i}{\sum_{i=1}^{n} \rho i}$$

Figure 9: Physical meaning of vector **vcg**

4.1. Properties of vector vcg.

- The vector **vcg** always points to the material. This property is usefull for defining and distinguishing the conflictive boundaries.

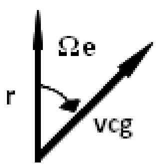
- In the case of continuum variables, the module of **vcg** will indicate if there is a boundary or not. The value of the module indicates how fast the variable varies in the direction of the vector (the maximum variation direction), hence, a high value of the module indicates that the existence of a boundary can be consider in that point.

High |vcg| = Boundary (drastic variation of the design variable)

Once **vcg** is obtained, we must know if there will be any manufacturing problem, and for that the growing direction of the structure must be defined. This direction is represented by the vector **r** which is defined by the designer.

r (designer defined) = (xr, yr) (2)

Now and for every 3x3 mask the angular deviation of **vcg** towards **r** is calculated. Summing these angels of deviation the number Ω is obtained, and every component of this number (the one of every mask) is called Ωe.



Ωe = deviation(**r**, **vcg**) (3)

$$\Omega = \sum_{e=1}^{m} \Omega e \qquad (4)$$

Figure 10: Physical meaning of Ω and Ωe

where m is the number of masks. Ω represents the probability for that a structure will need scaffold structures.

A typical situation in any topology optimization problem can be described as follows where problematic boundaries are painted in yellow.

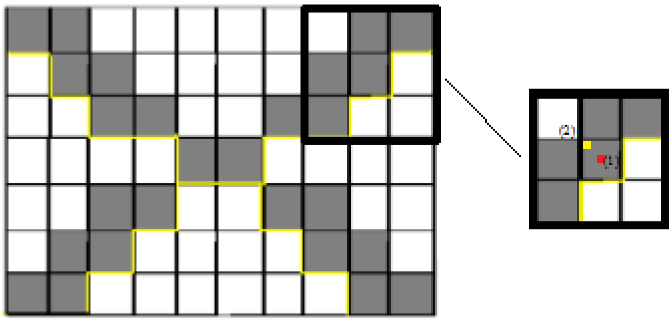


Figure 11: A typical situation in any topology optimization problem

In order to know if a boundary is critic we will use one of the components of its vector **vcg** and compare it with the correspondent of **r**. In this case we use the component ycg. As the vector always points the center of gravity, if the component ycg has the same sign as the component yr of vector **r**, that boundary will be conflictive.

$$ycg/yr < 0 \text{ -------- No problem}$$

$$ycg/yr \geq 0 \text{ -------- Conflictive boundary} \tag{5}$$

Then, in order to safe efforts, only in the case where $ycg/yr \geq 0$ we will proceed to calculate the deviation between the vectors **vcg** and **r**.

However, despite of being in the previous situation, the constraint is only (theoretically) violated if the relative angle y inferior to 45º, so it is helpful to relativize Ωe just to sum only in the cases where the constraint is really violated. Then,

$$\Omega o = \text{deviation}(\mathbf{r},\mathbf{vcg}) - \beta \tag{6}$$

where β is a parameter that represents the limit angle (45º in theory). As it's been mentioned, the overhang constraint is also affected by the member length, so we will let the designer defining the limit value for the angle from what the constraint will be considered violated. This way,

$$\text{If } \Omega o < 0 \text{ -------- The constraint is violated. } \underline{+1}$$

$$\text{If } \Omega o \geq 0 \text{ -------- The constraint is not violated. } \underline{+0}$$

Then, and remembering (4),

$$\Omega e = \begin{cases} 0, & \Omega o \geq 0 \\ 1, & \Omega o < 0 \end{cases} \tag{7}$$

$$\Omega = \sum_{e=1}^{m} \Omega e$$

This way, Ω represents not only the probability of needing scaffold structures or the amount that the constraint is violated, but also the number of conflictive elements. A high value of Ω means that there are so much elements that cannot meet the constraint and therefore that there is a high probability of needing some scaffold structures. Nevertheless, knowing Ω does not mean that we are capable of eluding scaffold structures, but it allows the designer to know more information about the amount of necessity for them.

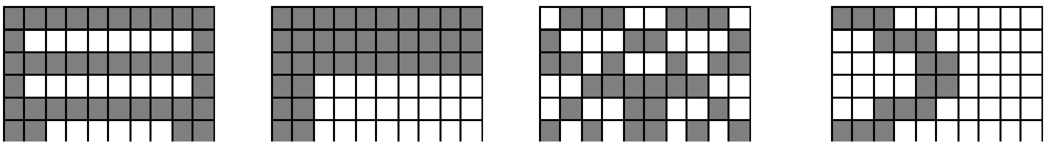
Another question is posed now and it is how to obtain a good interpretation of the number Ω. It's been explained that a high value of Ω means great violation of the constraint, but no information can be obtained beyond that. El objective of the authors is to detect and identify the boundary of every member y to be able to control their orientation, but this is presented as future work. [5] proposed a problem for minimizing the deviation Ωe, but the results didn't show any structural reliability, therefore the authors propose the development of new methods and techniques.

For having a correct interpretation of Ω a normalization parameter is needed, and that will be the perimeter, P. This way we can distinguish among cases that a priori possess similar value of Ω. For example, a structure with high value of Ω and a low value of the perimeter is a great problem due to the low amount of members and great amount of conflictive elements, but a structure with the same number Ω but high perimeter value, is a less critical situation. It is more critical a situation with a low number of holes (members) where vectors **r** and **vcg** will have the same direction in many continuum occasions creating thick members perpendicular to **r**, that one with a lot of little holes in it. For this reason, we define Ω as follows,

$$\Omega = \frac{\sum_{i=1}^{m} \Omega e}{P} \tag{8}$$

Having this information, the interpretation of Ω becomes easier and more effective.

$$\Omega \begin{cases} high \begin{cases} If\ P\ high = A\ lot\ of\ members\ but\ excesive\ constraint\ violation & \text{(a)} \\ If\ P\ low = Low\ amount\ of\ members\ and\ high\ violation & \text{(b)} \end{cases} \\ low \begin{cases} If\ P\ high = A\ lot\ of\ members\ and\ constraint\ violation, but\ can\ be\ self supporting & \text{(c)} \\ If\ P\ low = Low\ amount\ of\ members\ a\ little\ constraint\ violation\ . & \text{(d)} \end{cases} \end{cases}$$



(a) (b) (c) (d)

Figure 12: Representation of some examples

5. CONCLUSIONS

- Every typical parameter of the topology optimization problem has some effect on the complexity of the final geometry.
- Low values of the filter radius increase the complexity of the final topology, but the more complex design is not always the most suitable for additive manufacturing construction.
- Same geometry with different objective volume fraction can became non-suitable for additive manufacturing construction. As objective volume grows, member inclination tends to become more critical, specially in the boundaries.
- Objective perimeter shows the greatest effect on the complexity. Higher perimeters help creating more, shorter and thinner members. This effect can help avoiding the need for scaffold structures as the structure can become self-supporting.
- The number Ω represents the probability for that a structure will need of scaffold structures to avoid overhang constraint and be self-supporting. This information may help the designer interpreting how much the constraint is violated and evaluating the quality of the structure.
- The perimeter helps with the normalization of Ω. This parameter helps differentiating among cases with a priori the same value of Ω, giving more detailed and precise information.

REFERENCES

[1] E. L. Cardoso, J. S. O. Fonseca, *Complexity control in the topology optimization of continuum structures, J. Braz. Soc. Mech. Sci. & Eng.vol.25 no.3. Rio de Janeiro. July/Sept, 2003.*

[2] D. Brackett, I. Ashcroft, R. Hague. *Topology Optimization for Additive Manufacturing*, *August 17 2011.*

[3] C.S. Jog, M.P. Bendsoe, *A new approach to variable-topology shape design using a constraint on perimeter. Structural Optimisation 11, 1-12, Springer-Verlag 1996.*

[4] Smith S.M., Brady J.M. *SUSAN. A new Approach to Low Level Image Processing. Technical Report TR95SMS1c from Oxford Centre of Functional MAgnetic Resonance Imaging of the Brain.*

[5] Jens Fynbo, John Rasmussen, Niels Olhoff. *A Directional Topology Optimization Method. Institute of Mechanical Engineering, Aalborg University*.

[6] Andrew T. Gaynor, James K. Guest. *Topology Optimization for Additive Manufacturing: Considering Maximum Overhang Constraint. Johns Hopkins University, Baltimore, MD, 21218, USA.*

[7] M. Reuben Serphos. *Incorporating AM-specific Manufacturing Constraint into Topology Optimization. Faculty of Mechanical, Maritime and Materials Engineering. Delft University of Technology, May 30, 2014.*

[8] X.Y. Yang, Y.M. Xie, J.S. Liu, G.T. Parks, P.J. Clarkson. *Perimeter control in the bidirectional evolutionary optimization method. Structural and Multidisciplinary Optimization 24, 430-440, Springer-Verlang, 2003.*

[9] O. Sigmund. *A 99 line topology optimization code written in Matlab. Structural and Multidisciplinary Optimization 21, 120-127, Springer-Verlang, 2001.*

[10] Cristina Alonso, Osvaldo M. Querin, Rubén Ansola. *A Sequential Element Rejection and Admission (SERA) method for compliant mechanism design. Structural and Multidisciplinary Optimization 47, 795-807, Springer-Verlang, 2013*.

[11] Tomás Zegard, Glaucio H. Paulino. Bridging topology optimization and additive manufacturing. *Structural and Multidisciplinary Optimization, Springer-Verlang, 2015.*