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Topological optimization of internal patterns and support in additive manufacturing

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ABSTRACT

Rapid prototyping (RP) and more generally Additive Manufacturing (AM) enable the manufacture of complex geometries, which are very difficult to build with classical production. There are numerous technologies that are using different kind of material. For each of these, there are at least two materials: the production material and the support one. Support material is, in most cases, cleaned and becomes a manufacturing residue. Improve the material volume and the global mass of the product is an essential aim surrounding the integration of simulation in additive manufacturing process. Moreover the layer-by-layer technology of additive manufacturing allows the design of innovative objects and the use of topological optimization in this context can create a very interesting combination. The purpose of our paper is to present a methodology and a tool, which allow the use of topological optimization for the preparation of model for RP and AM.

1. Introduction

In the last decade, the use of structural optimization has rapidly increased. The upstream phases of design process represent 5% of the involved time of a product development, but engage 75% of the global development costs [34]. The integration of optimization in the early phases of a project is thus very important. The use of numerical simulation to optimize products has become essential to test different forms, materials, but also to better understand the involved physical phenomena. The main difficulty of using computational optimization is to manage the loops between CAD and CAE. Thus any change in geometry induced by the analysis can greatly increase the delay. Methods for shape optimization automate this chain and find an optimal solution with the inclusion of the specifications. Besides the possibility to test original solutions, the use of numerical optimization can address the problem of computing integration in the early stages of the design process. It is then necessary to establish a methodology for capitalization and knowledge management.

There are three main categories of shape optimization of mechanical structures [1]:

"Parametric shape optimization: the shapes are parameterized by a reduced number of variables (thickness, diameters, dimensions)." This class of optimization does not allow exploration of other possible shapes, but it allows to find (calculate) the optimum dimensions of parametric forms (existing forms of the model).

"Optimization of geometric shapes which, from an initial shape, vary the position of the boundaries of form." This optimization by the variation of the boundaries allows finding optimized contours structures without changing the initial topology.

"Topological shape optimization: obtain, without any explicit or implicit restriction, the best shape possible even if topology changes." This third category of optimization is an appropriate method for the design phase of a new part, because it can explore new concepts and solutions in areas of "no comfort" for engineers (see a basic example in Fig. 1).

The marriage between Additive Manufacturing (AM), which can build almost any shape, and topology optimization seems obvious. Indeed, the topology optimization will provide innovative forms but requires adaptation process from traditional manufacturing (typically a "remodelling" is required). The objective of this paper is to present the development of a methodology that will serve as a basis to develop a product that will be positioned upstream of the rapid prototyping machine. This software and the associated methodology are intended to be added on all types of AM machines. The material and mass saving obtained through the digital optimization can apply for plastics, metals etc. However one

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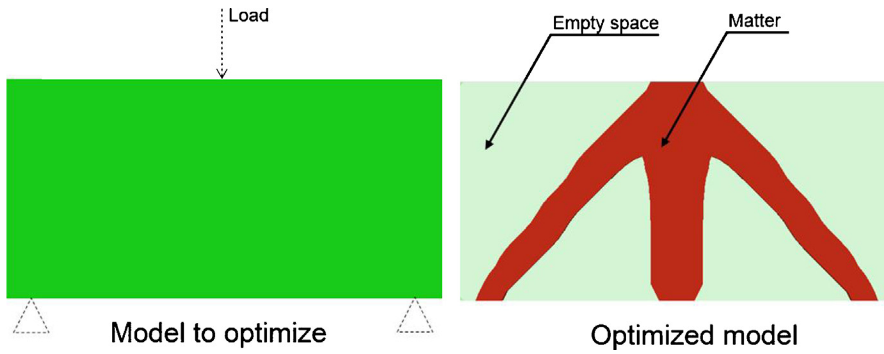

Fig. 1. Simple example of a topological optimization.

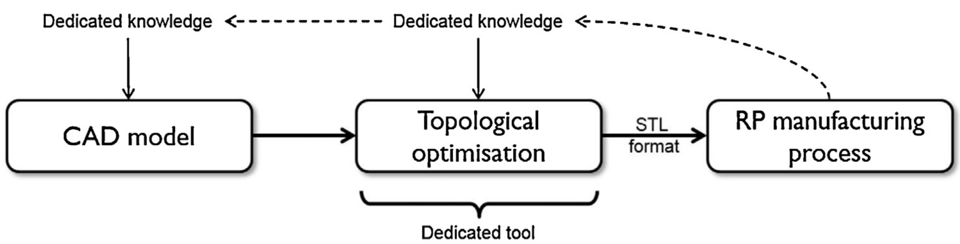

Fig. 2. Process of the project.

of the major interests of optimization in general and more specifically topological is to save mass on products. It is therefore natural to mainly target AM of steel products. In the context of AM centre NUM3D, we have access to a SLS machine type (Selective Laser Sintering). But the approach can be applied to another AM steel process like EBM (Electron Beam Melting), DMLS (Direct Metal Laser Sintering) etc. These different machining processes are brought together under the term ALM: Additive Layer manufacturing Metal application. Fig. 2 shows the positioning of the tool in AM process.

2. Related works

AM is nowadays widely used in industrial product development. The main advantage of the additive fabrication concept used in AM is the ability to create almost any possible shape. This capacity is governed by the built up layer-by-layer process. There are several available technologies based on this additive machining concept [2]: stereolithography, photo-masking, Selective Laser Sintering, Fused Deposition Modelling, 3D printing, etc. Researchers principally work on the influence of part orientation, slicing strategy, matching internal patterns to improve cost, product quality, built time, etc. Numerical topological optimization is a technical break that allows the modelling of really innovative shapes, based on trade knowledge. The next paragraph focuses on related works in the integration of optimization in AM. The second one, before a synthesis, presents topological optimization survey.

2.1. Optimization in additive manufacturing

The use of optimization in AM [3] is generally done into the context of optimization of the build direction [4], parameter optimization trades, and optimization construction layers algorithm and so on. The optimization of the quantity of material used is an important goal. This optimization can match both the product material and the support material. Fig. 3 shows the case of using a topology optimization on both the part and the support used (two optimizations are performed separately. Optimization in the "design" zone is the area that can be optimized, the "non-design" zone that cannot be changed).

AM machines generally offer the possibility of reducing the mass by using honeycomb shapes, lattices . . .. These algorithms model the simplified form without taking into account the specifications of mechanical strength. They are mostly applied for internal gain of matter. Actually, there are many researches on the influence of cellular structures. The influence of circular and rectangular shapes on the polyamide was studied through compression tests [5]. The study shows the influence of two types of geometric shape based on their use. The circular structure is able to absorb 43.5% more energy than a rectangular structure (very useful in high deformation rates for dynamic fast as crash, explosions etc.). Sugimura [6] investigated the use of lattice structures including rapid prototyping to lighten sandwich panels while maintaining their mechanical strength. The study enabled to determine the directions of the lattice anisotropy that influences the mechanical behaviour of the entire panel. The lattice modelling can be adjusted according to the specifications of mechanical strength. Other studies develop specific structures as curved [3], honeycomb [7], cell shape "tetrachirales" [8] or "hexachirales" [9]. However, these studies did not use the opportunity to integrate notion of mechanical strength. The topological optimization through numerical simulation can solve this problem. Ref. [10] shows the interest to integrate the topological optimization but also highlights some difficulties such as:

- The difficulty to manage the drainage system of the support part
- The size of the CAD file and the difficulty of implementation.

Recently [11] develops a methodology which allows the production of topological optimized part by a low cost FDM. This methodology uses the classic optimization process to optimize the mass of the part (included the skin of the part).

2.2. Topological problem specification

Topology optimization problem can be defined as the search for the best allocation or distribution of material in a given design

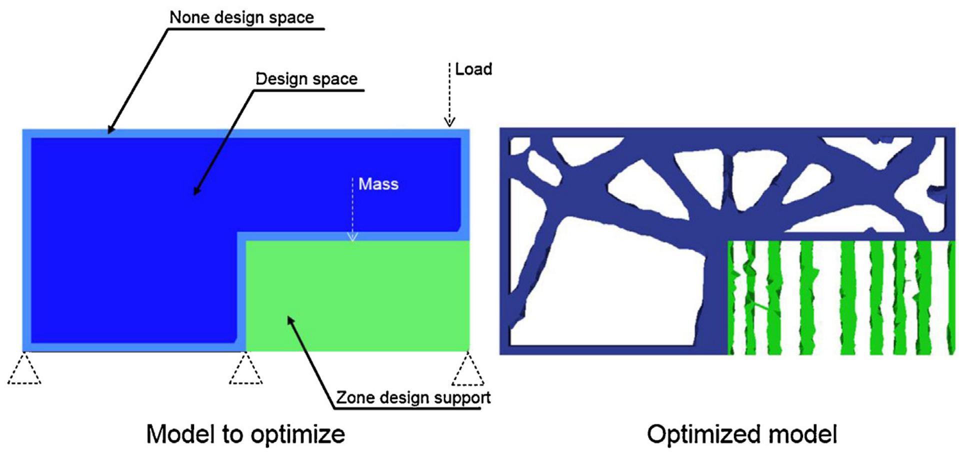

Fig. 3. Simple example of part and support optimization.

space [12]. The reference domain Ω ($\Omega \in R^3$) is determined by the design space, boundary conditions and loads. Ω is also chosen due to maximal available space. The aim is to find the best distribution of material i.e. determine the subdomain ω of Ω filled with the material. From a mathematical point of view, a topological optimization problem can be written as pictured in Eq. (1). We seek to minimize the objective function f within certain constraints to define χ.

$$\min_{\omega \subset \Omega} f(\omega) : [C] \rightarrow \omega \in \chi \qquad (1)$$

In practice the objective function may be represented by weight, volume, deformation energy etc., design variables by dimensions (thickness etc.), type of material etc. and constraints by displacement, mass, frequencies etc.

There are numerous methods for solving a topological optimization problem: derivative based and level set method, topological gradient method, homogenization method, evolutionary structural optimization, non-gradient methods etc. .... More information on all these methods can be found in Refs. [13,14].

We are particularly interested in homogenization method [15] and more precisely to SIMP (Solid Isotropic Material with Penalization) method. The basic idea of this approach was proposed by Bendsøe [16] and further developed by Rozvany et al. [17]. Actually, SIMP method has been applied successfully in several domains to obtain innovative structural design and was implanted in most topological optimization commercial software. The aim of the homogenization method is to transform a shape optimization problem into a problem of material density optimization (shape optimization by the homogenization method). This density has a value between 0 and 1 (0 = no material, 1 = material). For example, a density value of 0.2 will define a very porous material. A material density material is thus a continue problem (the density variable runs to the [0,1] interval) opposite to classic discrete optimization problem [18]. Basically, we replace the homogenized material by a fictive heterogeneous material. The homogenization algorithm calculates composite shapes and in mechanical skills "classic shapes" are needed. To help algorithm to frankly choose between empty material or full material, material characteristics are penalized (evolution of homogenization method to SIMP method). Indeed, the penalized method forces the density to take a value of 0 or 1. We can see in Fig. 4 the difference between using penalization or not on the classic plane stress problem called the MBB (Messerschmidt-Bolkow-Blohm) Beam problem (we take half of the MBB with symmetric conditions). This result is obtained thanks to MATLAB code developed by Sigmund [19] and more recently Andreasse et al. [20].

As said [14], the homogenization method requires a large amount of variables, making the implementation computationally expensive. One of the well-known problem of the SIMP method is that some intermediate densities have no physical meaning.

For a complete study between capabilities of different existing methods see [13] and [21]. This penalization point is very important in the SLS AM machining context. One example is the one who will drive the minimum thickness.

2.3. Synthesis

The majority of research mainly focused on the implementation of new forms (honeycomb lattice etc.) but uses little power topology optimization in numerical simulation that allows automatical modelling of the shape automatically. Knowledge management is however necessary to obtain innovative form in the trade context. It is important to note the necessity to manage the drainage system of the support part. As we have seen previously, using the SIMP method for topological optimization dedicated to rapid prototyping seems to be interesting. It requires an adaptation of modelling process and thus some work on knowledge modelling and its numerical integration. A methodology of application is also required. These points are discussed in the following sections.

3. Methodology

3.1. Introduction

A major interest of AM is to build parts or areas of parts that are not manufacturable by conventional methods (CN, plastic injection and so on). In the context of this research the goal is to optimize the quantity of material used. Optimization can be used in two cases in PR:

- all the part can be optimized (inner and outer – design and non-design space)
- the outer skin (or part of it) cannot be modified (due to functional/design specifications).

In the first case, we use the AM to obtain innovative shape. This concept is already well used in industry or research as well. As seen in the Fig. 5, topological optimization can be used for aeronautic part with an ALM AM process. The optimized design weighed only 326 g at the end, compared to 918 g in the original – a significant reduction of 64% [22].

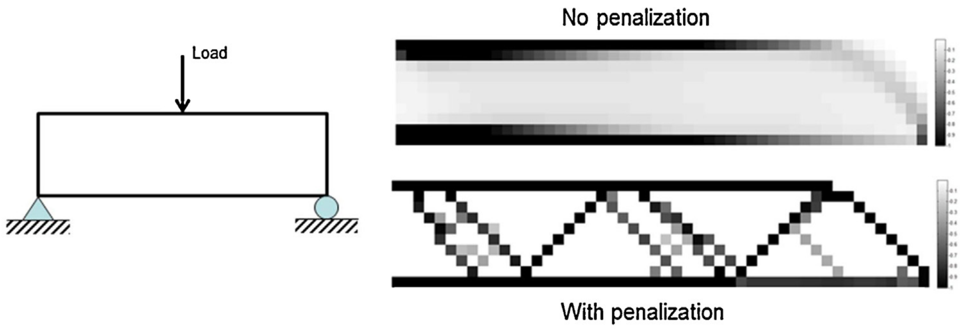

Fig. 4. Penalization comparison with SIMP model.

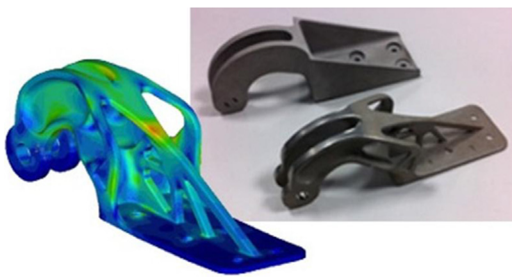

Fig. 5. Airbus A320 Nacelle Hinge Bracket (back) and the Optimized Design Produced by ALM (front) – Courtesy of EADS and ALTAIR.

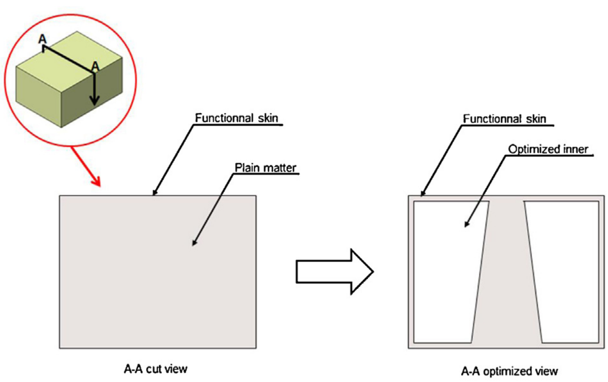

Fig. 6. Outline scoping illustration in a sample example.

It is important to note that many studies also use the power of optimization coupled with AM to work on completely and very innovative new form. In this way, Neri Oxman team [23] designs the engineering principles that will help to mature 3D printing into a technology able to produce complex structures inspired from nature. These biomimetic researches are also used in biomedical [24] to manufacture scaffolds for bone tissue. But as we saw on the state of the art section, the different works on the optimization of the inner are relative to find specific shape (like honeycomb). This paper deals mainly with second case namely works in the optimization of the inner part with a skin which cannot change (or few modifications like holes for the drainage system). As seen in Fig. 6, our aim is to optimize the quantity of material used in AM process.

Through the whole process, we take into account the fact that we need to evacuate support material at the end of the AM process. The slicing methods used by AM allow a very large variety of shapes (see Fig. 7).

The numerical integration of the constraint involved by the SLS process (typically DTM from 3D Systems) needs to manage the knowledge of the process to validate our concept.

3.2. Knowledge management

The integration of knowledge in numerical simulation is directly linked to the AM process knowledge and the optimization method used in finite element solver. The knowledge capitalization and modelization is done with specific methods developed on previous works [25]. We explain in the two next sections how we manage knowledge for topological optimization and for process AM machining.

3.2.1. Knowledge management in topological optimization

In topological optimization we try to solve a specific structural problem (as seen in Eq. (2)).

$$\min \sum_{i=1}^{n} \omega_i \left(\frac{f_i(x)-T_i}{T_i}\right)^2 g_j(x) \le 0 \quad j=1,m \tag{2}$$

In this equation, $f_i(x)$ are structural responses obtained from a classic Finite Element Analysis (FEA) and $f_i(x)$ are the constraints function. During the calculation, if $g=0$ constraints are active, if $g<0$ constraints are considered as inactive and if $g>0$ constraints are defined as violated (the calculation cannot reach the objective as well, defined by the target values T_i). The values of the weighting factors, ω_i are chosen by experiment, in order to obtain a suitable rapid and stable convergence of the scheme [15]. In topology optimization design variable are element densities (SIMP method). As we have seen before, specific techniques need to be introduced to penalize intermediate densities and to force final design to be represented by densities of 0 or 1 for each element. This particular adjustment is really important for the knowledge management. The penalization technique used is the power law representation of elasticity properties which can be expressed as shown in Eq. (3) where $\underline{K}$ is the penalized stiffness matrix, K the real stiffness matrix, ρ the density and P the penalization factor which has to be superior to 1.

$$\underline{K}(\rho)=\rho^P K \tag{3}$$

This penalized factor will have a very relevant impact on our problem. Indeed, in the case of AM, we have to manage the minimum length, which represents the thickness of the different walls. Belong to the machine process, this value is determined by experiment data. A basic example is shown in Fig. 8: on a simple C-CLIP optimization, the penalization factor management allows a bad or a good management of knowledge.

A topology optimization problem relative to AM process can be defined by:

- Design spaces: a *design space* corresponds to the interior of the objects and a *non-design* space corresponds to the skin of the

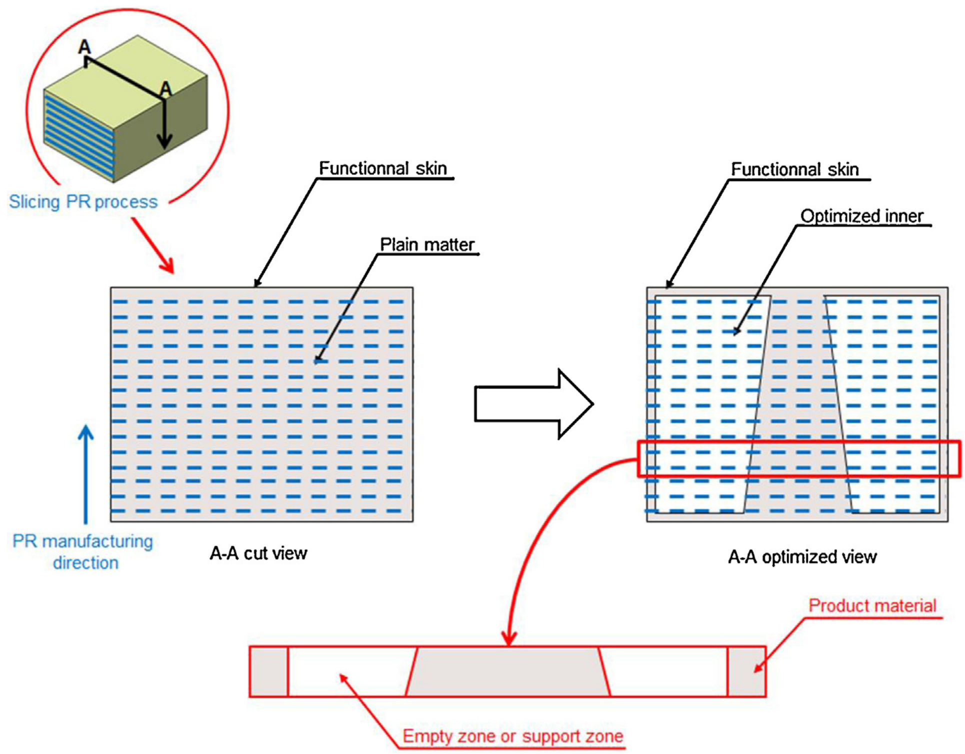

Fig. 7. View of the material benefit.

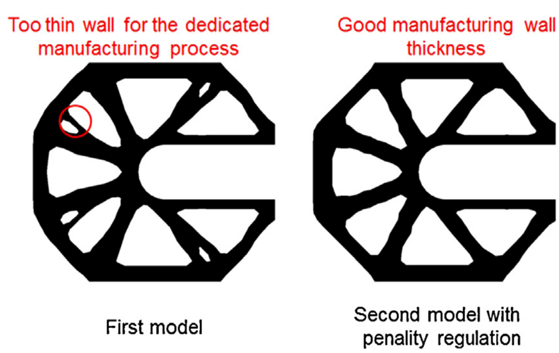

Fig. 8. Penalization factor management on a C-CLIP example.

object (or any other area that should not be modified such as the apertures for cleaning). These areas are identified in CAD model.
- Design variables: it is the set of parameters of the design space related to the AM process to define the initialization problem of topological optimization. We find here the penalization factor, the pattern repetition and so on.
- Responses: responses correspond to structural ones, calculated in a finite element analysis, or combinations of these responses to be used as objective and constraint functions in a structural optimization. Available responses could be for example static displacement, mass, volume, temperature, natural frequency, etc.
- Constraints: Constraints are based on responses by marking them with specific values
- Objective: The objective function is, as we have seen before, the minimization (or the maximization) of the problem, here a specific responses (for instance the aim is to manage one response by objective function).

3.2.2. Knowledge management in AM process machining

Selective Laser Sintering (SLS) uses a moving laser beam to sinter powdered polymer and/or metal composite materials into successive cross-sections of a three-dimensional part. Additional powder is rolled onto a platform, which support the successive cross-sections, from a reserve before building the layer. The powder is maintained at an elevated temperature so that it fuses easily upon exposure to the laser. Special support structures are not required because the excess powder in each layer acts as a support to the part being built. With the metal composite material, the SLS process solidifies a polymer binder material around steel powder (100 μm diameter) one slice at a time, forming the part. The part is then placed in a furnace, at temperatures in excess of 900 °C, where the polymer binder is burned off and the part is infiltrated with bronze to improve its density. The burn-off and infiltration procedures typically take about one day, after which secondary machining and finishing is performed [35]. One of the difficulties of this process is the transition between the AM process and the furnace. The part is breakable ("green part"). The knowledge investigation needs to take this characteristic into account. Note that with new AM process like EBM, solid metallic object is produced directly from metal powder. But this particularity doesn't change the concept of our proposition except for knowledge linked to the AM process.

Many researches [26–31] present a process of AM machine qualification by manufacturing a test part to quantify defects and grounds. However these approaches do not allow pushing to the technological limits of the machine.

This work aims to quantify the inherent defects in each process by the parallel between possible measures in metrology and process-related settings. Our approach is different (and complementary) since we determinate influential parameters and there are critical values according to using context, based on [32] research.

The experimental process to recover AM knowledge is based on two types of specimens

- iso campus norm ones manufactured by AM process: there aim is to recover material behaviour (typically elastoplastic law) to use

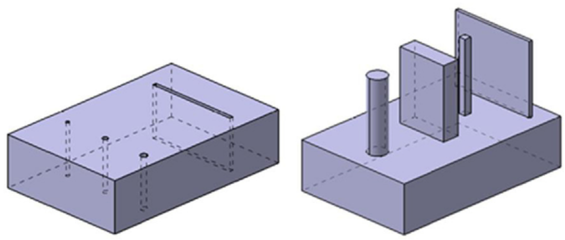

Fig. 9. View of the different method of manufacturing.

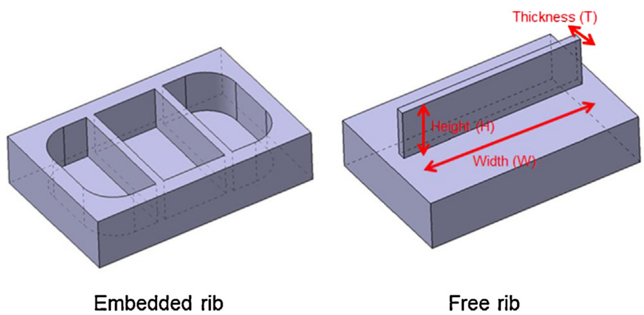

Fig. 10. Two kinds of tested rib features.

it in simulation. We use specific tools for the measure, for instance 3D Deformation Aramis camera.
- dedicated shapes ones also manufactured by AM process: there aim is to capitalize knowledge management like determine influences parameters: thickness/height limit, pocket depth allowed for powder evacuation, etc.

We can see in Fig. 9 different manufacturing direction and shape of the test parts. Those configurations allow the determination of risk factors.

Our approach involves the study of three very important factors for the topological optimization:

- The minimum thickness printable and cleanable without part deterioration. We seek to maximize the minimum thickness of the wire cloth (final material) without loss of geometric and morphological qualities of the part.
- The minimum diameter printable and cleanable without mechanical cleaning: the objective is to size the best channels dimensions for cleaning the internal structure of the piece (allow the powder evacuation).
- The maximum height, in fact the ratio between the projected length and height of the part which may cause a falling down of the matter.

We develop DOE (Design of Experiment) for different tests: test of the laser temperature impact, test of the thickness and height allowed (with cleaning process), test of the manufacturing orientation, test of the plate placement etc.

The tested material is a rapid steel metallic powder that is coated with a polymer. The SLS process involves many knowledge capitalizations because the part is involved in the laser phase, then debinding phase, then infiltration phase etc. Before the infiltration phase the part is very breakable and requires specific dimension management. The DOE is based on features analysis. Many features have been studied: holes, slots, ribs, pads, pockets etc. There are used in different context. For example the rib are studied in free way and in an embedded way. We define fourteen tests parts that include this feature (as seen for example in Fig. 10) and 3 DOE to drive the experiment. For example the first eight parts are dedicated to three specific features: vertical holes, slots, free and embedded ribs. The aim is to verify their manufacturability and ability to be cleaned up. The next algorithm presents a view of the different parameters used in one of the DOE.

The next tab shows the result for free rib, which are used in optimization parameters.

3.3. Process management

The different presented processes are found by tests inquiries and by CAD/CAE DINCCS research and development centre experience. Indeed we argue that an inductive approach is further interesting in research. Be able to have industrial back up is very useful to capitalize knowledge and to test the different methodologies. In return, industrial applications become very relevant due to the association of researches. The first step of our methodology is to identify and define design spaces (see Fig. 11). A boolean operation in CAD software is needed to delimit the different zone. In our application, knowledge is linked with Rhinoceros software to help the designer in different important factor (like thickness of the skin which are linked with the specific AM process). The knowledge is dependant on to two major factors:

- the calculus set: the part is maybe subjected to specific set like loads, use impact (modal analysis for example) etc. This item is not necessary, if the part to be manufactured is just for design view (touching function, assembly integration, etc.) the only set will to not fall down on his own mass
- the AM process corresponds to previous detailed knowledge capitalization. It depends on the AM machine.

When the part is optimized (see details below), we add space shape for the support matter cleaning. This shape is pre-designed in CAD software and positioned in empty spaces (for instance in a manually way). We obtain in results a STL file that is put in the AM machine process software.

The optimized step is also defined as sub methodological process (see Fig. 12). The first step is to define design variables like the penalization factor as we explained before. This penalization factor is defined according to the minimal thickness obtain by test. We define then two specific responses:

- compliance response. The compliance is the strain energy of the structure and can be considered as a reciprocal measure for the stiffness of the structure. A global measure of the displacements is the compliance of the structure under the prescribed boundary conditions (see Eq. (4) with K the stifness matrix and U the displacements)
- fraction of mass response. The fraction mass response is the material fraction of the designable material mass. It corresponds to a global response with values between 0 and 1. This allows the user to specify intuitive question like “I want to gain 30% of mass”, value transcribe as 0.3 in our programme.

The next step is to minimize the compliance. Generally, in optimization, the compliance is used to evaluate the stiffness. Minimize the compliance means to have a stiffer structure. The lower the compliance is, the higher the stiffness of the structure will be. So, the problem statement involves the objective functional of the strain energy which has to be minimized.

$$C = \frac{1}{2}U^T KU \tag{4}$$

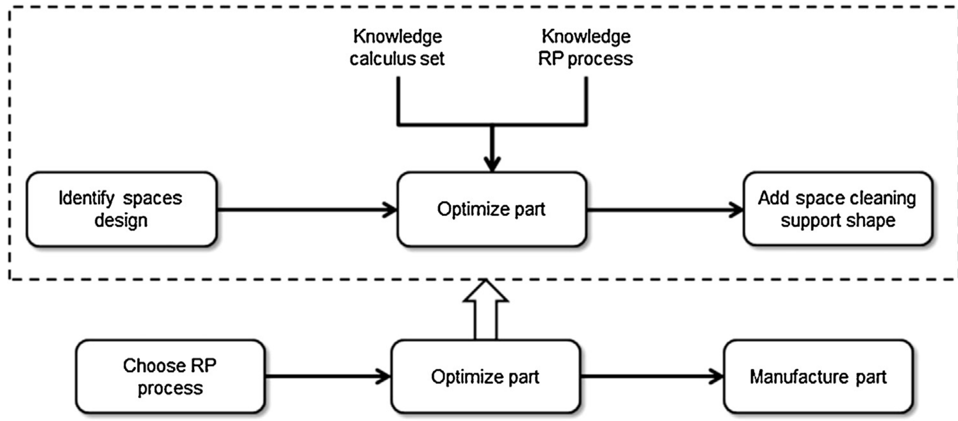

Fig. 11. View of global methodology.

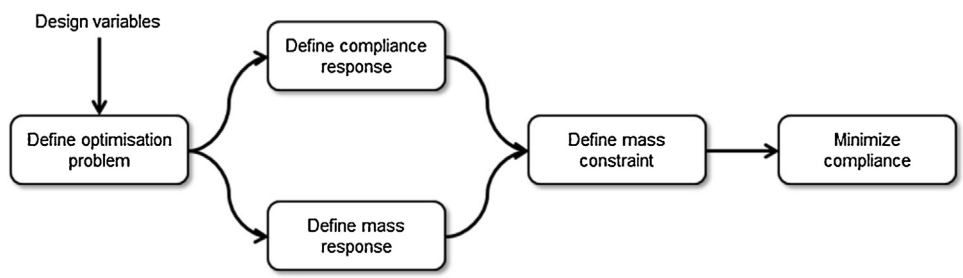

Fig. 12. View of optimization methodology.

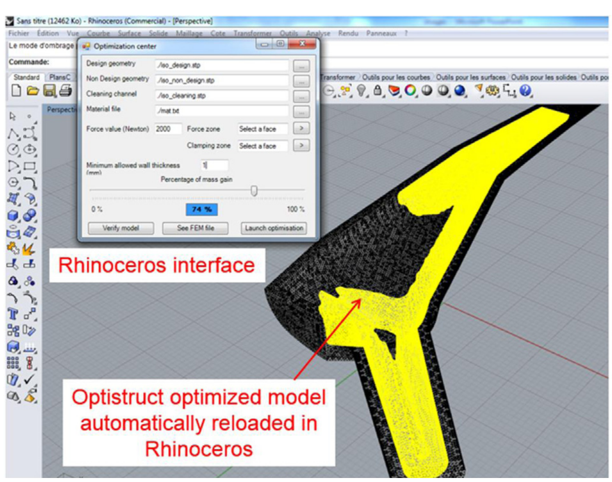

Fig. 13. View of Rhinoceros programme and half of the hip model.

Table 1
Results for rib doe analysis.

Parameter	Operator	Value	Result
Thickness	<	1 mm	Non feasible (matter collapsing)
Thickness	=	2 mm	Deformation for height >10 mm
Thickness	=	3 mm	Deformation for height >40 mm
Width	>	15 mm	Cleaning constraint
To help the global strength, pins can be brought back			

4. Application

To validate our methodology and prepare the software integration, we first verified our assertion with commercial software. We developed in Rhinoceros 3D an interface which helps the designer to prepare the CAD model and launch in background Optistruct (Altair) solver (see Fig. 13). The programme is developed in python. We study a prosthetic implant used in a hip replacement surgical procedure studied for one of our client (a simplify one with regard to the confidentiality). There are a large number of hip implant devices on the market. Many different shapes exist but each styles fall into one of four basic material categories metal on plastic, metal on metal, ceramic on plastic and ceramic on ceramic. Due to the history of our region (large of foundry and forge industrial impact), we are interested in the metal on metal material and more particularly on titanium. This kind of prosthesis is built with forge process in titanium material (Table 1).

Previous work enabled us to integrate knowledge to CAD model. The modelling is based on a specific methodology [25] that covers the knowledge capitalization and modelling using scripts [33]. The programme which supports the methodology is developed in python and is dedicated to the preparation of optimization model namely:

- load the design and non-design CAD model (step format). The design part matches to the skin of the part and the non-design part matches to the allowed modified space
- load the cleaning channel. One the limited function of the system is the fact that the user cannot load more than one channel for the moment
- load the material file which is a simple txt file which contains all the basic information for the simulation. For the moment the system only integrates linear simulation. Table 2 shows parameters used for the hip example
- define the calculus load and boundary condition. The user has to enter the force value and select two faces: one for force application and one for clamping application. A multiple point constraints (RBE2 type) is automatically created based on the node of these two faces

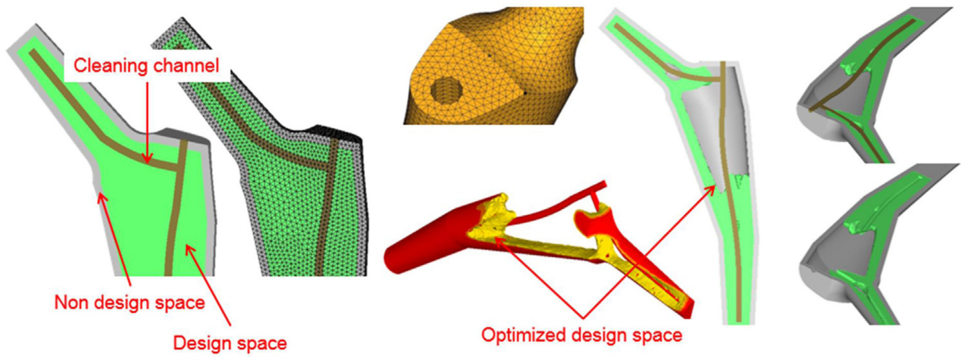

Fig. 14. View of the interior of the hip after the optimization.

Table 2
Titanium linear material card.

Name	Ta6V
Rm	860 MPa
Rp 0.2	780 MPa
A	10%
E	110 GPa
Poisson coef.	0.3
Density	4.5e−09 t/mm^3

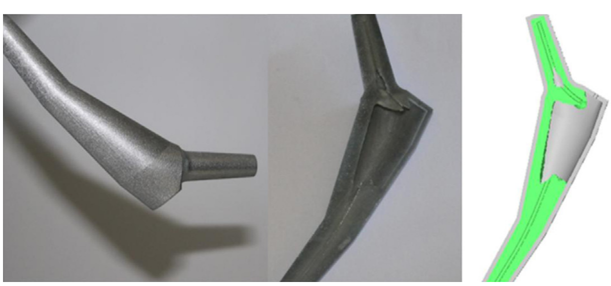

Fig. 15. View of manufactured hip right out of the oven.

- define the optimization knowledge based on the process described in previous paragraph namely the minimal allowed wall thickness and the percentage of weight gain.

Once these parameters are set, the user can verify the model (the system makes a basic verification before running), check the fem ascii file (this file is the entry for Optistruct solver; it has been automatically created by the system by creating in background a mesh (with hypermesh) and link it with user parameters; note that for instance the mesh is based on global size of the part) and run the optimization. After the optimization, the result is reloaded by the system on Rhinoceros to view it. The exported model is on STL format. If the user is ok with the optimization he can load the STL result on his AM machine. You can see in Fig. 14 the optimized result by asking a 30% of weight gain.

The hip has been manufactured on the STS machine in two versions: a full version for physical test and a half version for academic purposes (see Fig. 15). The weight gain is almost around 25% in comparison of the 30% of the simulation.

5. Conclusion and future trends

We explore the possibility of using topological optimization in RP and more generally in AM. We are particularly interested in the optimization of the inner part. The aim is to optimize the volume of material to be used and the global mass. The developed methodology and the associate tool are presented in this paper with a steel part example. The weight gain is indeed more simple to explain but the methodology was tested in more than ten parts with different AM process: FDM, SLS and SLA. The methodology allows the conservation of the outer skin and the optimization of the inner part.

For instance, the integrated knowledge in the developed tool in Rhinoceros is basic: one of our current jobs is to help more the designer to define different parts according to the knowledge capitalization. The optimization solver is for the moment the commercial software Optistruct. The aim is to integrate in front office of the RP process a tool which automatically optimized the part to product. Indeed we began the development of a tool with the help of Code-Aster finite element software (distributed under GNU GPL licence). One of our difficulties is for FDM and SLA process to indicate to the machine what is support material zone or not.

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References

[1] Thakur A, Banerjee AG, Gupta SK. A survey of CAD model simplification techniques for physics-based simulation applications. Comput Aided Des 2009;41:65–80.
[2] Wohlers T. Additive manufacturing and 3D printing – state of the industry. In: Wohlers Report 2012. Annual worldwide progress report. 2012.
[3] Galantucci LM, Lavecchia F, Percoco G. Study of compression properties of topologically optimized FDM made structured parts. CIRP Ann – Manuf Technol 2008;57:243–6.
[4] Phatak AM, Pande SS. Optimum part orientation in rapid prototyping using genetic algorithm. J Manuf Syst 2012;31:395–402.
[5] Vesenjak M, Krstulović-Opara L, Ren Z, Domazet Ž. Cell shape effect evaluation of polyamide cellular structures. Polym Test 2010;29:991–4.
[6] Sugimura Y. Mechanical response of single-layer tetrahedral trusses under shear loading. Mech Mater 2004;36:715–21.
[7] Abramovitch HM, Burgard Lucy Edery-Azulay, Evans KE, Hoffmeister M, Miller W, Scarpa F, et al. Smart tetrachiral and hexachiral honeycomb: sensing and impact detection. Compos Sci Technol 2010;70(July (7)):1072–9.
[8] Miller W, Smith CW, Scarpa F, Evans KE. Flatwise buckling optimization of hexachiral and tetrachiral honeycombs. Compos Sci Technol 2010;70(July (7)):1049–56.
[9] Prall D, Lakes RS. Properties of a chiral honeycomb with a Poisson's ratio of −1. Int J Mech Sci 1997;39(March (3)):305–14.
[10] Rochus P, Plesseria J-Y, Van Elsen M, Kruth J-P, Carrus R, Dormal T. New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation. Acta Astronautica 2007;61(June (1–6)):352–9.
[11] Rezaie R, Badrossamay M, Ghaie A, Moosavi H. Topology optimization for fused deposition modeling process. Proc CIRP 2013;6:521–6.
[12] Calvel S. Conception d'organes automobiles par optimisation topologique. Université Paul Sabatier Toulouse III; 2004.

[13] Rozvany GIN. A critical review of established methods of structural topology optimization. Struct Multidiscip Optim 2009;37:217–37.
[14] Garcia-Lopez NP, Sanchez-Silva M, Medaglia AL, Chateauneuf A. A hybrid topology optimization methodology combining simulated annealing and SIMP. Comput Struct 2011;89:1512–22.
[15] Bendsøe MP, Kikuchi N. Generating optimal topologies in structural design using a homogenization method. Comput Methods Appl Mech Eng 1988;71:197–224.
[16] Bendsøe MP. Optimal shape design as a material distribution problem. Struct Optim 1989;1:193–202.
[17] Rozvany GIN, Zhou M, Birker T. Generalized shape optimization without homogenization. Struct Optim 1992;4:250–2.
[18] Allaire G, Jouve F. Structural optimization by the homogenization method. In: Argoul P, Frémond M, Nguyen QS, editors. IUTAM symposium on variations of domain and free-boundary problems in solid mechanics, solid mechanics and its applications. Netherlands: Springer; 1999. p. 293–300.
[19] Sigmund O. A 99 line topology optimization code written in Matlab. Struct Multidiscip Optim 2001;21:120–7.
[20] Andreassen E, Clausen A, Schevenels M, Lazarov BS, Sigmund O. Efficient topology optimization in MATLAB using 88 lines of code. Struct Multidiscip Optim 2011;43:1–16.
[21] Bulman S, Sienz J, Hinton E. Comparisons between algorithms for structural topology optimization using a series of benchmark studies. Comput Struct 2001;79:1203–18.
[22] Tomlin M, Meyer J. Topology optimization of an additive layer manufactured (ALM) aerospace part. In: The 7th Altair CAE technology conference. 2011.
[23] Oxman N. Variable property rapid prototyping. Virtual Phys Prototyp 2011;6:3–31.
[24] Arafat MT, Lam CXF, Ekaputra AK, Wong SY, Li X, Gibson I. Biomimetic composite coating on rapid prototyped scaffolds for bone tissue engineering. Acta Biomater 2011;7:809–20.
[25] Danesi F, Gardan N, Gardan Y, Reimeringer M. P4LM: a methodology for product lifecycle management. Comput Ind 2008;59:304–17.
[26] Bernard A, Fischer A. New trends in rapid product development. CIRP Ann – Manuf Technol 2002;51:635–52.
[27] Kochan D, Kai CC, Zhaohui D. Rapid prototyping issues in the 21st century. Comput Ind 1999;39:3–10.
[28] Kruth J-P, Leu MC, Nakagawa T. Progress in additive manufacturing and rapid prototyping. CIRP Ann – Manuf Technol 1998;47:525–40.
[29] Scaravetti D, Dubois P, Duchamp R. Qualification of rapid prototyping tools: proposition of a procedure and a test part. Int J Adv Manuf Technol 2008;38:683–90.
[30] Childs THC, Juster NP. Linear and geometric accuracies from layer manufacturing. CIRP Ann – Manuf Technol 1994;43:163–6.
[31] Olivier-Patrick T, Alain B. Study of a standard part for layer manufacturing processes, in European Conference of Rapid Prototyping and Manufacturing, Athènes; n.d.
[32] Lee BH, Abdullah J, Khan ZA. Optimization of rapid prototyping parameters for production of flexible ABS object. J Mater Process Technol 2005;169:54–61.
[33] Gardan N, Gardan Y. An application of knowledge based modelling using scripts. Expert Syst Appl 2003;25:555–68.
[34] Sharpe JEE. Computer tools for integrated conceptual design. Des Studies 1995;16:471–88.
[35] Goban Ján, Semančík Marián, Lazoríková Táňa. Manufacturing of forms for injection moulding technology by rapid prototyping method. Int J Eng Ann Faculty Eng Hunedoara 2013;11:195–7.