RODIN project, Topology Optimization 2.0?

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RODIN project, Topology Optimization 2.0?

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Abstract: RODIN project is an attempt to propose a new kind of topology optimization tools. It has been motivated by the combination of two events: (1) the industrials demands for getting past serious limits identified in the available tools, (2) the advent of a new mathematical approach in the mid 2000’s presenting very interesting properties. This project has been launched in July 2012 and is supported by French public funding. It is a collaborative project that gathers ten partners (ranging from academics to software editors and industrials end-users) and firmly aims at overcoming technical and scientific locks in the area of topology optimization. RODIN is therefore an ambitious and risky project that will possibly mark the birth of a new numerical tool.

Keywords: Topology Optimization; Level-set method; CAD return; manufacturing constraints.

1. Introduction

In the area of shape optimization, the topology approach has become very popular. The huge number of papers dedicated to this technology attests to this craze both from industrial and academic sectors.

Topology optimization consists in finding the optimal material distribution within a design space (i.e. the available volume). Up to the early 2000’s, one main technology, Homogenization and its variants (power-law, SIMP method) have been proposed (see [BK.88], [Ben.95], [ABF.97], [All.01], [DS.03]). The SIMP approach (Solid Isotropic Material with Penalization) has been implemented into many commercials tools (NASTRAN, OPTISTRUCT, GENESIS, PERMAS, etc). Topology optimization has deeply changed the way to design. The standard methodology has long relied on the experience of designers and on their ability to guess the optimal load path. They usually distribute the material in a way to maximise the stiffness regarding given excitations. It must be noticed that even for a simple component, the experience will greatly make the difference between several competitors. Each of them will differently understand and interpret the mechanical system and finally set a “personal” design. Among all the feasible designs that individual designers may create, one of them is yet the best regarding for example mass savings subject to stiffness constraints. Whatever the component, it will then be produced in large quantities, in particular in the car industry, hence the utmost importance of systematically reaching the best design regardless of the designer. In this context, topology optimization has brought a very promising and unexpected response.

RENAULT was not among the pioneers in the use of topology (see [Ra.00], [Jeo.02], [Ree.02], [BH.03], [Mey.05]). Initial attempts date back to the early 2000’s but the first serious studies have been performed afterwards, in the framework of internal research project. One of those studies focused on the accessories bracket, a massive component that is part of the powertrain. It is clamped in the block cylinder and bears compressor and alternator. The first part of the study consisted in defining the set of specifications to meet that turned out to be an unexpectedly complex task. In a standard process, designers always propose a robust enough initial shape that engineers just have to validate (numerically or physically). The amount of material expended is often so large that the component would be capable of withstanding a large range of fictitious excitations. On the contrary, optimization process aims at removing unnecessary parts given the requirements of the optimization problem and at delivering the leanest feasible design. In order to avoid unexpected removal, the formulation of the optimization problem must be complete.

The accessory bracket is not deeply complex (it is mainly a matter of stiffness and eigenfrequency, and the geometry is not especially challenging). Any experienced designers should easily propose an efficient solution that topology optimization would probably not be able to outperform. Nevertheless their solution was far heavier than the one computed by the topology optimization tool. One may further assume that the benefit could supposedly be even more substantial for increasingly more complex problems. Indeed, humans are not capable of fully appreciating the entire logic of a large set of specifications (eigenfrequency, stiffness, frequency responses, etc) that will often act in antagonist ways. From the industrials point of view, the practice of topology optimization seems quite light (compared for example to parametric optimization) and promises to systematically deliver the leanest solution no matter the complexity of the problem, hence its natural appeal.

Five years later, many studies were launched on several components (accessories bracket, engine mount, wheel, knuckle, housings, oil pan, etc.), led by different people and based on more or less updated versions of commercial tools. Unfortunately, the conclusion is not as optimistic as expected: the benefits are not so systematic and to this day RENAULT still struggles to massively deploy the technology. It was decided to make a diagnosis which is detailed in the following section.

The three parts of this paper will be devoted respectively to the genesis of the project, the description of the deliverables and finally to the presentation of the results obtained so far.

2. Motivations of the RODIN project

2.1 Our diagnosis

Topology optimization is attractive for many reasons:

- The execution is very simple compared for example to parametric optimization. There is no need to define a set of parameters: whatever the method (CAD or morphing), this task is burdensome, time-consuming, requires very specific knowledge and skills, and deeply depends on the designers. Furthermore there is no need to automate the computation workflow, a task that also demands rare know-how. By contrast, topology optimization requires only the definition of a design space (or working domain) that approximatively takes into account architectural constraints (i.e. presence of other components).
- The set of solutions is far larger than for any kind of parametric approach that logically leads to better solution. In parametric or sizing optimization, the dimension is given by the number of parameters and typically ranges from 1 to 100, rarely more. In comparison, topology optimization evolves in far bigger dimension, more than 100.000 if one considers for example the density per element as degrees of freedom.
- The solution does not depend on the user any more. This is exactly the opposite in parametric optimization since human choose parameters that will greatly influence the final solution. In topology, only the design space will impact the result and is only constrained by architectural matters.
- The mass-saving can be significant depending on the specificities of the optimization problem: it may range from 3% to 15%.
- Time savings are also achievable in principle but are much more delicate to assess.

Despite these advantages the deployment remains modest. Within the SIMP framework implemented by virtually every commercial software package, it seems difficult to further enlarge the scope of applications for topology optimization. The method is often used for approximately designing simple components such as accessories bracket, engine mount, and so on, but engineers still struggle to devise a robust methodology dedicated to more complex components. It’s partly due to the following serious limits:

- Inability to deliver an industrial design: The solution often looks more like a rough concept than an industrial design. Even though the clever distribution of material can guide designers towards a feasible geometry, this last step still requires deep experience. The mismanagement of manufacturing constraints partly explains the inadequate result.
- Inability to manage surface criteria: for NVH considerations, it is useful to control the displacement, velocity, acceleration or pressure on the boundary. Even in standard mechanical analysis, controlling the maximum stress level, in practice often reached on the boundary, is a significant design constraint

- Inability to support design dependent loads such as pressure, temperature, heat coefficient, etc.
- Inability to export a clean mesh of the solution: At the end of the optimization process, it will be very useful to export an unambiguous definition of the shape in order to help designer generate a CAD model, or simply to validate the result.

2.2 Our analysis

Roughly speaking, topology optimization mainly consists in removing unnecessary parts of the design space. It has been done by virtually removing elements that do not participate to the stiffness of the structure. In effect, these are assigned a null density. On the opposite, the set of elements with full density (i.e. 1) will compose the optimal topology with an unambiguous frontier. This problem is combinatorial in nature and therefore technically impossible to manage for all but trivial settings. With “only” one thousand elements in the design space, the number of configurations reaches two raised to power one thousand, i.e. 1.0e+300!

To overcome the curse of dimensionality, it has been proposed notably in the SIMP method to relax the problem by allowing the density in each element to vary continuously (see [DS.03]). This trick paves the way to the introduction of the machinery of differential calculus. The sensitivities with respect to the density per element contain information required to tackle a problem of such magnitude. The calculation of the derivative relies on the adjoint method that consists in judiciously introducing an auxiliary variable (the adjoint state) that alleviates the need to explicitly evaluate the derivative of the state variable. Many applications are based on that approach.

By contrast with the combinatorial problem, the SIMP approach makes the problem manageable but does not lead to a clear solution, i.e. exclusively composed of 0/1 density elements. Unfortunately, there are a lot of intermediate densities that require the users to manually adjust where the interface lies. The consequences are:

- Users have to devise the most probable density threshold that will round up and down all the intermediate density. If it wasn’t the “good” value, designers and engineers will waste a lot of time to redesign and evaluate an uninteresting shape.
- Whatever the threshold, a lot of unconnected parts often remain, requiring to clean the result and postponing further the validation process.
- The absence of sharp boundary explains the difficulty to handle manufacturing constraints. These are often related to geometric criteria (e.g. thickness, distance, etc.) which rely on the knowledge of the accurate location of the boundary. Otherwise the implementation of such criteria may require sometimes poorly specified treatments based on more or less justified heuristics.
- A similar reasoning applies to design dependent loads and all sorts of surface criteria.

2.3 Opportunity

Since the early 2000’s, new technologies have been considered, in particular the “Level-set Method” (see the seminal work of G. Allaire and F. Jouve [AJT.02]). Many research initiatives have been launched since then around the world proving the interest of this new technology ([AJT.04], [WWG.03], [DMLK.13]). Academic results have demonstrated the feasibility of this approach and its relevance to topology optimization. This is also a key motivation for the RODIN project.

Roughly speaking, this method relies on three main ingredients (see [AJT.02]).

First of all, an original mathematical description of the shape is introduced.

Let a bounded domain $D \subset IR^d$ be the design space in which all admissible shapes Ω are included, i.e. $\Omega \subset D$. This domain is meshed uniformly once for all. The boundary of Ω is parametrized by means of an auxiliary function, the so-called “level-set” function, as originally proposed by S. Osher & J.A. Sethian (see [OS.88]):

$$\begin{cases} \varphi(x) < 0 \Leftrightarrow x \in \Omega \\ \varphi(x) > 0 \Leftrightarrow x \in D \setminus \overline{\Omega} \\ \varphi(x) = 0 \Leftrightarrow x \in \partial\Omega \cap D \end{cases}$$

For any point in the working domain, this function returns a negative (resp. positive) value if it belongs to (resp. lies outside) the shape and zero if it lies on the boundary. Since there is an infinite set of functions that meet those characteristics, another property has been added:

$$|\nabla \varphi(x)| = 1 \qquad [1].$$

It makes this function unique and behaving like a signed distance function.

The second ingredient pertains to the way to govern shape modifications.

This operation is based on the so-called Hamilton-Jacobi time-dependent equation:

$$\partial_t \varphi + V|\nabla \varphi| = 0 \qquad [2]$$

where “V” denotes the normal velocity at which the shape boundary moves.

Assume that the shape $\Omega(t)$ evolves in time $t \in IR^+$ with a normal velocity $V(t,x)$ then:

$$\varphi(t, x(t)) = 0, \forall x(t) \in \partial\Omega(t)$$

which leads to :

$$\begin{aligned} d_t\varphi(t, x(t)) &= \partial_t \varphi + \dot{x}(t).\nabla \varphi \\ &= \partial_t \varphi + Vn.\nabla \varphi \\ &= \partial_t \varphi + V|\nabla \varphi| \\ &= 0 \end{aligned}$$

where $n = \dfrac{\nabla \varphi}{|\nabla \varphi|}$

The third ingredient is the determination of the normal velocity.
We rely on the notion of “shape derivative”, which goes back to Hadamard, and has been fully developed by many others mathematicians (see [MS.76], [Pir.84], [Cea.86], [SZ.92]).

In the Hadamard method, starting from an initial reference shape Ω, deformed shapes are parametrized by a vector field ϑ and denoted Ω_ϑ.
The deformed shape is defined by:

$$\Omega_\vartheta = \{x + \vartheta(x), \forall x \in \Omega\}.$$

In other words ϑ is the displacement field which moves Ω to Ω_ϑ.

An important result states that the directional derivative only depends on the normal component of ϑ on the boundary. Let us give one example to highlight the idea.

Define the objective function:

$$J_1(\Omega) = \int_\Omega \phi(x)dx$$

with $\phi(x)$ “sufficiently” smooth.

The shape derivative is then:

$$J_1'(\Omega)(\vartheta) = \int_{\partial\Omega} \phi(x)\vartheta(x).n(x)ds$$

for any smooth $\vartheta(x)$.

The formula becomes significantly more complex in presence of state variables stemming from static linear analysis or other state equations. Nonetheless, the philosophy remains unchanged.

3. Organization

3.1 Partners

CMAP, ESI and RENAULT are the initiators of this project. Natural partners have then joined the final consortium:

- Three academic partners who are in charge of tackling scientific and theoretical issues: CMAP (Applied Mathematics at Ecole Polytechnique, Palaiseau, France), UPMC (University of Pierre and Marie Curie, Paris, France) and INRIA (Bordeaux).
- Four software editor partners who are in charge of implementing numerical solutions: ESI (experts in Virtual Product Engineering, editor of PAM-CRASH,PAM-STAMP, ProCAST...), DPS (specialist in CAD issues), ALNEOS (specialist on FEM) and Eurodecision (specialist on optimization).
- Three industrials partners who are notably in charge of specifying the needs: RENAULT (car maker), AIRBUS and SNECMA (aeronautic industry),

3.2 Deliverables

The deliverables of the RODIN project are:

- A topology optimization tool based on the level-set method: TOPOLEV. This software relies on SYSTUS, a ESI proprietary software package that performs the mechanical analysis. The scope of analysis ranges from linear analysis in a broad sense (static linear, modal analysis, frequency responses, thermal) to non-linear analysis (contact, material non linearity, large deformation). This perfectly covers a large scope of industrial needs.

- A FEM translator: SYSTUS is largely used in nuclear industry but not in car industry. During the project, ALNEOS has performed comparisons in order to validate the software. The most important task of ALNEOS was to enrich their VEGA platform that is a sort of “Rosetta Stone” dedicated to finite element modelling. This tool is capable of interpreting an initial FE model specified in a virtually arbitrary format, translating it into an abstract internal language and finally generating equivalent mechanical model for any other solver. Thanks to this tool, engineers do not need to become intimately familiar with SYSTUS, and can continue to work with the software of their choice while VEGA “automatically” translates the model in the native format of SYSTUS.

- A mesh export tool: After performing a topology optimization, one is often interested in validating the solution, especially to ensure that it conforms to the specifications that could not be taken into account in the optimization problem. Since the main focus is topology optimization, the solution is only approximatively captured by the set of elements with full density. The creation of a tightly fitted mesh of this solution is made possible thanks to the level-set description but requires a dedicated mesh generator.

- A CAD return tool: As much as possible, the RODIN project aims at providing integrated solution. The last industrial demand is the capability to come back to the designer environment, i.e. CAD. The last deliverable is a CAD return tool that aims at transforming a mesh into a CAD geometry. DPS is in charge of that task.

3.3 Challenges

Many challenges have been identified and some of them are detailed below:

- It has been previously explained that the level-set approach would be more adapted to tackle manufacturing constraints since the boundary is clearly identified. Nonetheless, some research effort is necessary to formulate adequate criteria, to assess the shape derivative and finally to implement those constraints in an optimization process.
- Another concern pertains to the set of specifications that industrials desire to take into account. Most are based on linear analysis (static or modal) but some depend on non-linear analysis (boundary, material or geometric). In any case, the steps are: (1) formulate the criterion (if needed), (2) assess the shape derivative and (3) embody it in the optimization process.
- The “CAD return” is another big issue. This is an industrial demand that will greatly help the deployment of topology optimization tool. “CAD Return” means the ability to generate a CAD model on the basis of topology optimization result (characterized for example by a mesh). This task is nowadays performed by a designer and takes several days. Reducing that delay is a requirement to embed topology optimization more efficiently into the design process. Generating a CAD is a time-consuming process and doubly so if starting point is just a concept without sharp boundary and the manufacturing constraints have not been efficiently handled. Thanks to the level-set approach, the solution should be closer to an industrial shape even if no tool that automatically converts a mesh into a CAD does exist.

3.4 Program - way of work

As a first approximation, there are two kinds of activities within the project: research and implementation.

“Research activities” encompass scientific, numerical and theoretical issues:

- Formulation of new criteria: this is notably the case for the work package devoted to the manufacturing constraints. The task consists in establishing precise mathematical formulations for the different manufacturing rules.
- Shape derivative: The effective treatment of many criteria involved in the requirements of industrial use-cases implies the evaluation of the associated sensitivities. This is partially the case for static, modal analysis and frequency responses. Most of useful criteria have already been managed. Regarding nonlinear analysis (notably contact) some positive and promising results have been produced within the framework of a PhD thesis.
- Some of those previous criteria require a specifically tailored treatment in the process of optimization.

As to implementation:

- The first task was to implement the level-set machinery. This mainly includes the redistanciation operator (i.e. the resolution of the eikonal equation [1]) and the advection operator (i.e. the resolution of Hamilton-Jacobi equation [2]). Those two equations respectively manage the renormalization of the level-set function and the shape deformation given a velocity. The optimization algorithm was another routine to develop. Some research effort was also necessary to tackle this issue.
- The assessment of the (geometric or mechanical) criteria was another task. Very intrusive changes in the mechanical software were required for some of them. It is a delicate and deep challenge but it ensures to have a consistent and efficient tool. Nonetheless, the key challenge is the computation of the shape derivative. For virtually all the mechanical criteria, the implementation and the resolution of an adjoint problem was required.
- The last task but not the least is the development of a user-friendly workflow. The

role of this interface is to hide as much as possible the complexity and to make the topology optimization process as straightforward as possible for non-experts.

4. Results

4.1 Standard optimization

The first use-case proposed by RENAULT is an engine mount. This component is clamped on the powertrain (both on the cylinder block and the head cylinder) and on the opposite side is fixed on the vehicle. Its role is to support the powertrain and to limit the amount of excitations that go through and produce unpleasant vibrations for passengers. The set of mechanical specifications includes some stiffness constraints, eigenvalue positioning and frequency responses considerations. This use case is largely representative of many components.

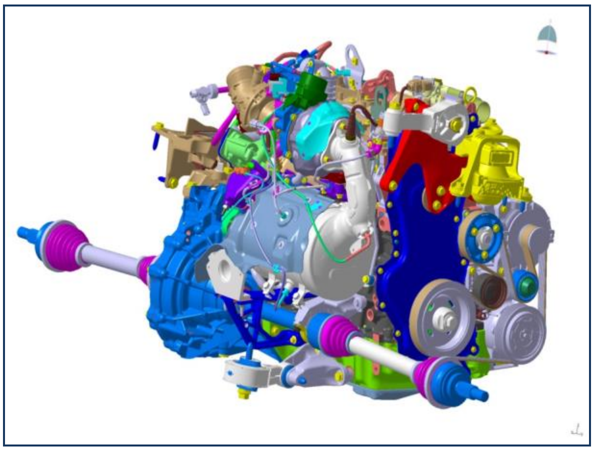

Fig 1: the engine mount (in red) is clamped on the powertrain and fixed on the vehicle.

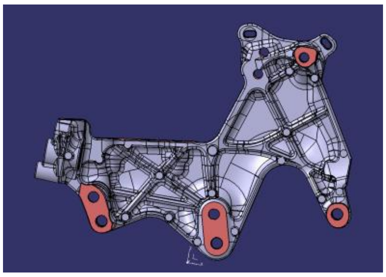

Fig 2: the CAD geometry

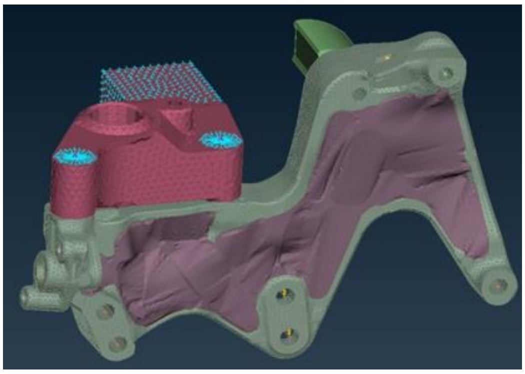

Fig 3: Focus on the engine mount. The core has been filled in order to enlarge the design space.

For this first study, only the core of the engine mount (purple part in the above figure) is the design space for topology optimization.

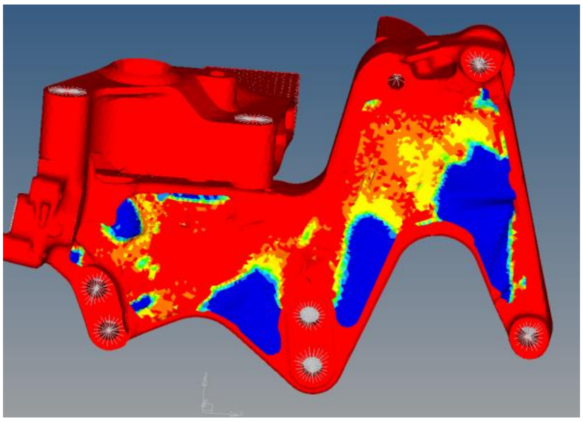

Fig 4: Solution with SIMP

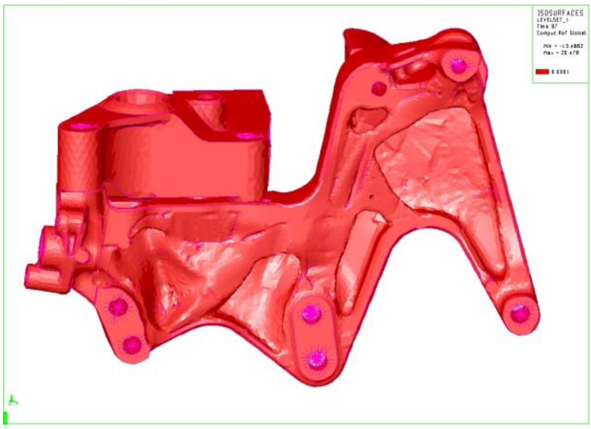

Fig 5: solution with TOPOLEV

Since a vertical load has been applied in a remote point (at the end of the second components), the optimizer has logically created members that prolong the load path until the fixed points. Unfortunately, the shape presents many cavities.

By contrast with the SIMP approach (cf figure above), absolutely no intermediate density appears in the solution. The shape is clearly defined and will more likely help the designer to generate the final geometry. It is even clearer when manufacturing constraints are also considered.

4.2 With molding constraints

Among all the manufacturing constraints, this one is probably the most important.

The foundry process consists in three stages:

- The “filling” corresponds to injecting liquid aluminium inside de the mold. Thanks to a compressor system the process is over after only a few seconds. However, the thinner the members are, the more powerful the compressor needs to be. In addition to the increased energy consumption, doing so would weaken the mold. Therefore in order to avoid premature malfunctions, members of the shape should not be too thin. In other words, there is a significant benefit to add a geometric constraint in the optimization process based on the minimum thickness. This functionality will be added in TOPOLEV. Theoretical material has already been produced (see [Mic.14]).
- The “cooling” corresponds to the solidification of the aluminium. Thanks to the cooling system (by air or water), this stage takes only a few seconds as long as some conditions are met. When the structural members are too large, two problems may occur. The first one is the creation of porosity due to the shrinking of the material that deteriorates the performance of the system. Besides, the duration of the solidification increases until it becomes incompatible with the process. To avoid this situation, another geometric constraint is required based on the maximum thickness. This functionality was added to TOPOLEV. The theoretical contributions are also due to [Mic.14].
- The “mold removal” consists in moving apart all the molds and comes with another set of restrictions In particular, no cavity must exist in the shape. This criterion has been added in TOPOLEV (see [Mic.14] for theoretical issues).

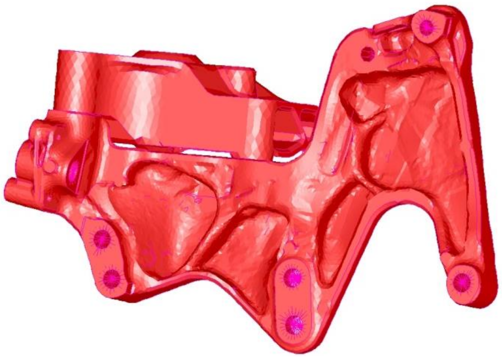

Fig 6: with the molding constraint

The integration of the molding constraint deeply changes the shape of the engine mount. While the load paths are barely affected, the optimal result is slightly heavier but is cavity-free. A new step towards a more industrial solution has been achieved.

4.3 Maximum thickness

The feasibility of the approach was shown on an academic use-case. The demonstration on industrial use cases (e.g. engine mount) will occur later.

The working domain is a unit cube clamped on his lower feet. An unit load is applied on the lower face. The optimization problem is to minimize the mass under some stiffness constraints (compliance, displacement, etc).

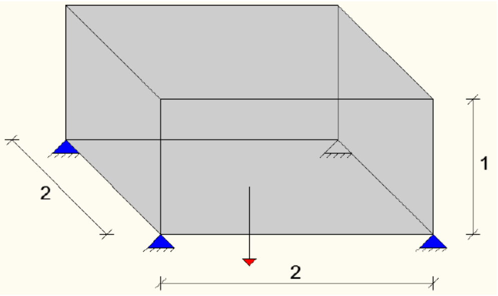

Fig 7: the design space is a cube, clamped on the four bottom feet, and a load is applied in the middle of the lower face.

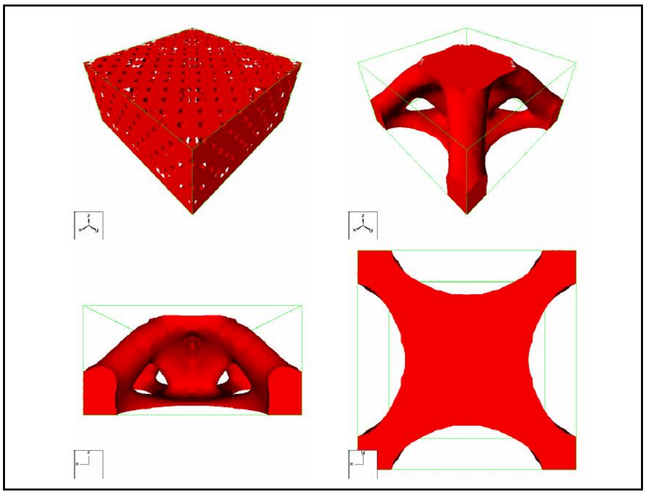

Fig 8: Without maximum thickness.

Without the thickness constraint, the shape presents large and cylindrical arch-like members. The appearance drastically changes as soon as the thickness constraints are taken into account. In order to maintain the same stiffness level, the optimizer has chosen to divide all the cylindrical arches into thinner bars. This is exactly what is expected for an industrial component.

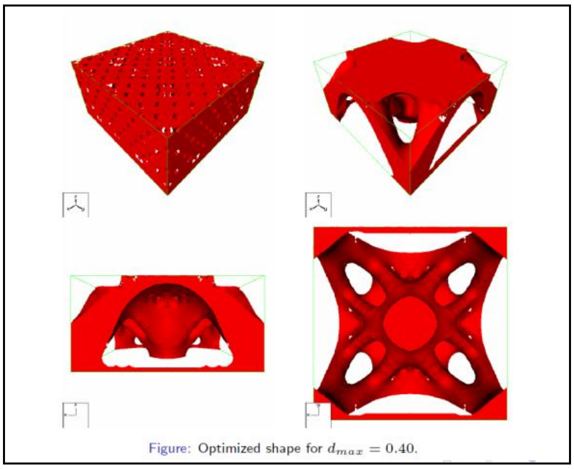

Fig 9: with maximum thickness

4.4 Additional academic results

Among all the criteria requested by the industrial partners, one of them required very specific developments: von Mises stress. The latter is widely used by designers to check whether their design will withstand a given load condition. From a mathematical point of view, this criterion is much more difficult to handle since it is a pointwise criterion (i.e. defined on every element of the mesh).

Some successful preliminary studies have been carried out on several academic use-cases. One of them is presented below.

Consider the famous L-shape use-case. It is clamped on the upper face whereas a unit load case is applied on the opposite face. The aim is to minimize the volume subject to stiffness and von Mises constraints.

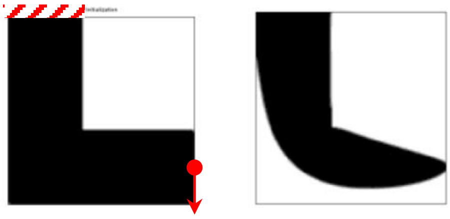

Fig 10: (left) initialization, (right) optimal shape without von Mises

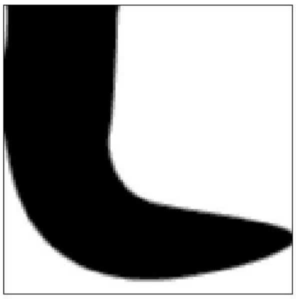

Fig 11: optimal shape with von Mises

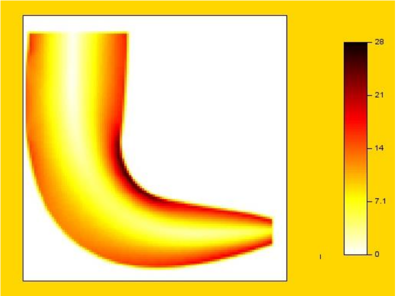

Fig 12: von Mises level

The maximal acceptable value for the von Mises (30) is perfectly respected. Besides, those results highlight that designing a mechanical part with stress in mind may entail more than local modifications.

4.4 CAD return or “reverse engineering”

The ability to manage the CAD return has been proved on a standard and well-known academic use-case, i.e. the 3d cantilever.

The workflow can be described as follows:

- A topology optimization is first performed. The problem consists in finding the optimal shape that minimizes the volume (or mass) subject to stiffness constraints (compliance).

- A mesh is then generated with a numerical tool that was developed internally. As described earlier, the boundary of the shape is characterized by the iso-zero of the level-set function. The creation of the mesh consists in splitting all elements cut by the iso-zero. This will automatically create a closed surface mesh that perfectly respects the shape. However, since the quality of the mesh obtained by the above process is very poor, a subsequent remeshing step must be performed. A volume mesh has also been generated. This work is due to C.Dapogny and P.Frey (see [Dap.13], [ADF.13]). Their remarkable contribution goes much further and will be probably detailed in another paper.
- Creation of the CAD model. The input is the previous surface mesh.

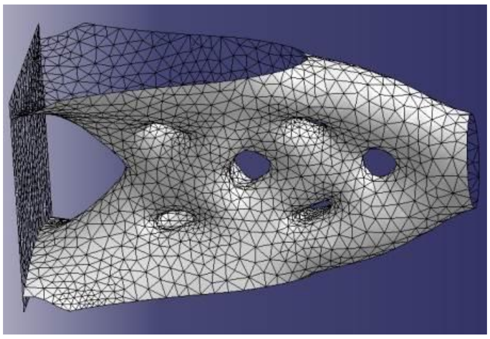

Fig 13: surface mesh of the topology solution

To perform the CAD return on the basis on a surface mesh, DPS has tested several tools (commercial or not). One of them ("tool A") has largely outperformed all the others (see the next picture). To emphasize the difference, we have also put the result obtained from another tool ("tool B").

Four criteria have been taken into account to gauge the quality of the CAD model:

- Respect of the geometry: this is the ability to fit patches on the original surface. This is a necessary property but not a differentiating one since every tool has been capable to generate quite reliable solutions.
- Smoothness: along the shape, no spurious change on the curvature must appear. This property is noticeably not respected in the last result.
- Parsimony: some tools have created so many patches that it is difficult to load the model in a CAD environment. Parsimony means the ability to create a CAD model with an adequately small number of patches.
- Sampling: This property partially refers to the previous one. This is the ability to "cleverly" dispose the patches. On this specific point, the first result clearly outperforms the second one.

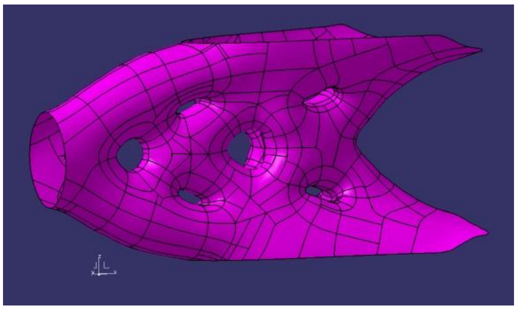

Fig 14: CAD model provided by "tool A".

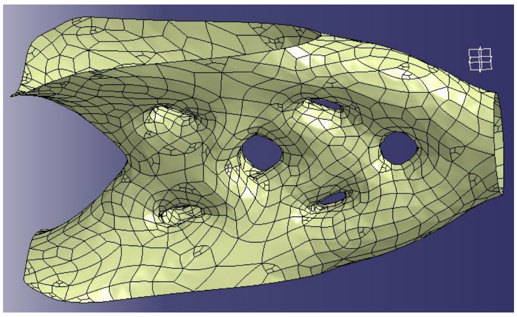

Fig 15: CAD model provided by "tool B"

5. Conclusion

The integration of new functionalities keeps going:

- About manufacturing constraints: the integration of the minimum thickness is ongoing. This is the last core feature that industrial partners need. The theoretical background has already been completed and a proof of feasibility has been achived, although a fine tuning of the optimization process would be probably necessary.
- Mechanical criteria based on linear analysis: the implementation of new criteria is naturally continuing in the area of static linear analysis, modal analysis and frequency responses.
- Mechanical criteria based on nonlinear analysis: for the time being, the work remains exclusively theoretical although some encouraging results have already been produced.

- Mesh export requires further care in order to deliver a robust and powerful embedded workflow. However the theoretical work is essentially complete for this topic and only implementation issues remain.
- CAD return: the solution is mature.
- FEM model conversion: the VEGA platform is also mature. Additional functionalities will be naturally added.

A few years after the beginning of the RODIN project, the consortium has demonstrated that the Level-Set approach method is perfectly capable to manage “real world applications”. The consortium reasonably hopes that a first commercial tool will be delivered in the course of 2015.

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8. Glossary

NVH: Noise, Vibrations and Harshness