Management and Economics Design Optimization: Fundamentals and Case Study

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***Abstract*- To remain competitive in the globalized world, Small and Medium Enterprises (SMEs) need to create and design structures that are cost-effective and consistent with specific mechanical performance. In this paper, we are interested in the economical impact of numerical optimization and the necessity to define a new management of the design process.**

The linear process of design-engineering-manufacturing is nowadays obsolete. Even DFX (Design For X) methodologies are often replaced by Simulation for XFD (X being also Design) approaches. Optimization is also often applied before design. For instance, engineering design optimization of mechanical structures is nowadays essential in the mechanical industry (automotive, aeronautics ...), but optimizing mechanical structures cannot be efficient without taking in account other phases of the design-manufacturing process. In some cases, optimization is only based on trade knowledge.

Engineers must design parts or assemblies that are a better compromise, between mechanical and functional performance, weight and manufacturing costs, etc. This paper gives a brief overview on different disciplines in design optimization of mechanical structures through an "automatic" approach. We propose a new methodology to integrate numerical optimization in a functional design process, which can achieve huge economical gains as demonstrated by two industrial examples in this paper.

Keywords- ***Design Optimization, Methodology, Process, Economical Gains***

I. INTRODUCTION

Firms have always faced the problem of continuous improvement of their structures in order to predict the optimal forms and structures in the early stages of design. The best compromise between economic, technological and mechanical parameters has always been the number one objective of the mechanical engineer.

In the research of this compromise, working methods have changed considerably in recent years. Hardware performance, associated with the new methods for solving optimization problems, leads to new methodologies in the design phase.

SME's designers are often in-house engineers with little knowledge about simulation. The process is based on a CAD phase followed by a validation phase, which leads to three fundamental characteristics:

– it is a "try / error" approach, which necessitates costly engineer time and does not ensure the best economical solutions ...

– prototypes are still often manufactured instead of implementing simulation processes: even if additive manufacturing can be used in some cases, this prototyping phase must be avoided as often as possible

– numerical optimization is not used :

It is a fact that even if the optimization of mechanical structures and parts is taken into account, it has for a long time been based on a " try / error" methodology. This approach leads to test prototypes whose design is based on the experience of the engineer [1]. It is customary to design structure first, then calculate and possibly optimize, therefore the classic stages of design sizing are obtained as follows:

– The achievement of one or several CAD models from the experience of engineer,

– The implementation of various calculation models (static, vibration, dynamic etc.) that assess the various design criteria of the structure.

– Several iterations to change the design in order to meet the specifications and optimize the structure.

In the above stages, the point of economy is ignored, or if taken into account, mainly based on the experience of the user. Moreover, different parts of an assembly can be developed by different engineers, each one trying to manually optimize its work. This can lead to local optimization but it reveals not to be global optimization and economically adapted, and even the integration of a PLM (Product Life-cycle Management) cannot avoid these defaults, due to the fact that their implementation does not recognize enough details in the product.

It is also important to note that the user experience leads to some kind of known solutions in main problems, even if the manufacturing process, the material or even the capacity of the CAD/simulation/optimization software should permit new innovative solutions.

In a globalized world, it is now mandatory to optimize the product and its environment. The mechanical engineers now are required to integrate the optimization of mechanical structures in their first design phases. This new approach integrates the design requirements and the specifications such as manufacturing constraints, constraints related to business processes, thermo-mechanical performance, weight requirements and cost. The engineers can then automatically reproduce, through modeling and numerical optimization software, the work that a designer manually achieved, by adding many advantages :

- Opportunity to scan a wider design space.
- Possibility to implement Design of Experiments and thus create approximation functions if needed.
- Ability to reach an optimum by using more efficient algorithms.

These " automatic " methods can find optimal solutions for mechanical structures even if the reference [2] thinks that " in real life, identification of the optimum design of an industrial problem is often not possible because of the size and lack of knowledge".

That's why in many cases just a part of the optimization problem is processed, for example, the design optimization of mechanical structures.

In the "real life", it is very dangerous to leave aside the influence of optimization on the manufacturing process.

Obviously, the results of a mechanical structure can lead to a more costly product due to a complex manufacturing process, or even, the impossibility to manufacture.

So, optimization cannot only be considered in terms of mechanical structure, which can generate more costs (not known by the designer, for example during the manufacturing process) and thus is against the economical point of view.

Anyway, the gains from the optimization of structures will be illustrated by taking into account the entire process but the technical details will be ignored as it can be found in [3]

After a brief presentation of methods and techniques for optimization, two industrial examples will be presented to show economical gains.

II. THE NECESSITY OF A "SYNTHETIC" APPROACH

Before describing optimization methods, we introduce a "global" vision of the design-manufacturing that we call "synthetic", based on the fact that local optimization does not always contribute to global performances.

The main one in design is based on the mechanical structures optimization and for example deterministic and probabilistic methods or evolutionary algorithms. After presenting the main methods, the knowledge methods will be illustrated in the next section by an example.

Our research intends to define a global model which places the process module in the center of the DMU (Digital Mock-Up). Process module manages proceeds which modify the product. Our methodology is working on a hierarchical framework presented in [4]. This framework allows a top-down approach by defining functions in a high abstraction level and refining them in a low abstraction level.

The 4 ‘P’s are defined according to

- Project module represents all the entities related to the organization, the resources (human and equipment). Project module is defined in the Application Environment.
- Product module represents all information which characterizes product contents in a systematic way. A product has different representations according to the predefined abstraction levels.
- Proceed represents abstracted definitions related to a sequence of physical or virtual steps which lead to the modifications of the product.
- Process represents a succession of tasks whose implementation contributes to the modification of the product.

Whenlooking at an optimization problem, it is important to take into account the trade. So it is suggested to use a formalized methodology to model and maintain the trade knowledge, respecting the following phases:

- detect the interesting knowledge (ontologies ...)
- extract it (human aspects ...)
- model it (structure, modeling ...)
- approve it (norms, homologation ...)
- open it (at the disposal of the users or the programs ....).

This is a permanent process, the detection phase becoming a maintenance phase, verifying whether the knowledge changes or not and so on.

To implement the adapted CAE (Computer Aided Engineering) systems, we must take into account trade knowledge. It is by an integration of trade knowledge in the CAD (Computer Aided Design) system or in the specific developed software modules that we achieve our goal to improve the performance of the user.

Much work has been done on knowledge management. We emphasize on two main points:

– Ontologies: we think that it is very powerful to base the work on ontologies. This means that during the analysis phase of a new industrial problem, we use our internal tools (developed in EEP4LM project) to define the domain ontology, which ensures that the things are well defined between the end-user and us. We don't develop this point in this paper.

– We also introduce the notion of Graphonumerical Numerical Parameter (GNP). The computer representation is ''action_object(constraint/parameter)''. A user can define a GNP like ''create_hole(-through)(diameter)'' which is the translation of ''create a through hole with diameter'' (a specific syntax has been developed for an intuitive use [5,6]). This GNP is linked to a scenario which defines this GNP. When a GNP is applied, the system constructs an implicit parameter which is the link between GNP and trade rules or constraints. For the precedent GNP, an implicit parameter called ''diameter_- hole'' is created. A link is done with the KBS (Knowledge Based System) if a rule or a constraint has a similar parameter. The following section presents how a GNP is decomposed according to the hierarchical architecture. A GNP has a different representation in each level of the hierarchical architecture of the KBS.

When a new application is taken into account, we use P4LM approach and specific tools.

First, we study different processes and define the ontology. Then we look at commercial tools used (or that could be used) and make specific developments, according to our methodology and our tools.

Even if we study the overall numerical chain to ensure that a local optimum does not contribute to a global optimum, we are mainly interested in well closed steps of the design process in which the trade knowledge modeling can lead to important gains in quality, cost or delay.

This kind of application, with a development effort between a few days and weeks, depending on the complexity of the product and data, produces significant benefits, including: quote achieving very quickly (virtually of instantaneously), reliability of choices (quote is validated by the entire chain, including simulation, rather than just vague evaluation); if the contract is obtained, the design is "almost" complete.

As a consequence, the formalization process (P4LM, ontology) is very interesting for the company, even if the software itself is not implemented. Many examples show that the design / manufacturing process, assumed perfectly controlled by the firm, is only very known to be imperfect and often has different implementations based on operators or shadow areas. This preliminary study may need improvements, sometimes even without software development. It is important to remain attentive to the consistency of approach compared with the global numerical chain and developments to undergo software (changes in materials, new practices, standards, etc.).

In order to work with small and medium sized firms, we have developed a collaborative tool (Adhoc Collaboration). Its description is not a purpose of this paper, but it is interesting to know that this collaborative tool (asynchronous and synchronous …) has been immediately adopted without any problem even by very small firms.

For example, CAD4SIM (CAD FOR SIMulation) [6] defines the rules to help industrial firms, to better design in order to better simulate products. Therefore, rules are definedto be used during the design process (automatically or manually), thus ensuring correct simulation.

III. MECHANICAL STRUCTURES OPTIMIZATION

We are mainly interested in the economical influence of design optimization and the management of dedicated new design processes. The methods for solving optimization problems (deterministic, stochastic, etc.) can be found in [3] which is not a focus of this paper. However, as it is necessary to have a good idea of the different methods, we give an overview of the implementation in optimization software.

In terms of mechanical engineering, three major kinds of design optimization are considered: *Parametric, Geometric, Topological.*

A. Parametric Design Optimization (Size)

Shapes are parameterized by variables like sections, thicknesses, diameters, length etc. This optimization does not give the possibility to explore new forms but it is only used to size the existing forms. A beam is considered to illustrate this kind of optimization.

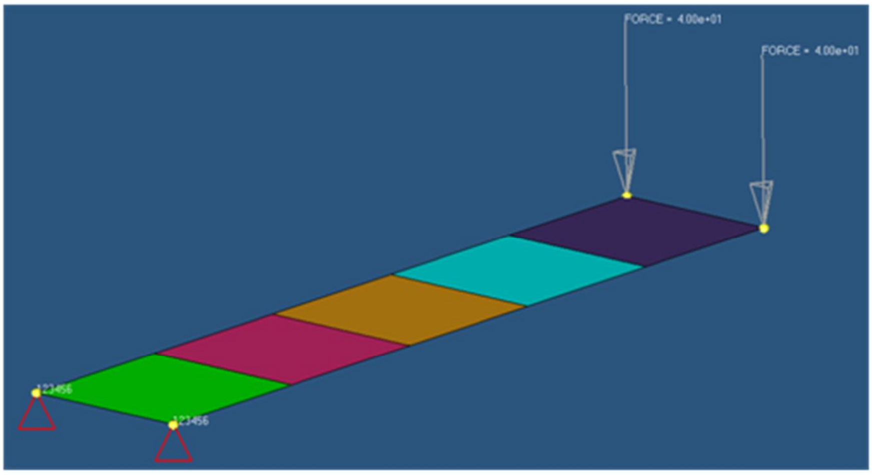


Figure 1. Initial Beam

The optimization problem is to optimize the Mass of the beam. In this example, the thickness for each element (5 elements) can vary.

Therefore, the optimization problem is to minimize the structural mass and allow a limited vertical deflection of the loading end. The displacement is limited to 2.0mm. All thickness variables have a lower bound of 1mm and an upper bound of 3mm.

Then the mathematical problem is: Minimize (Volume) with constraint.

- 1mm < thickness < 3mm (for every element)
- Maximum displacement < 2mm

In this simple case, we have obtained a gain of 5.5% of mass respecting the maximum allowable displacement for the beam.

B. Geometric Design Optimization

Geometric design optimization is used to vary the boundaries of an original form without changing its topology. Changing the boundaries of the geometry requires updating the mesh. This remeshing is produced in the optimization process.

To illustrate this class of optimization, we consider the example of a plate embedded at one end and the other is subject to a force. The optimization is implemented by using a free shape optimization.

The optimization problem is to maximize the stiffness of the plate by changing the shape of the curve defined by the selected nodes in Figure 2. The thickness of the plate remains fixed. We also want to have the X displacement of the application’s point of the force below 0,1mm and the Y displacement below 0,08mm. The formulation of the problem is: Minimize (Compliance) with displacement constraint:

- X displacement < 0.1
- Y displacement < 0.08mm

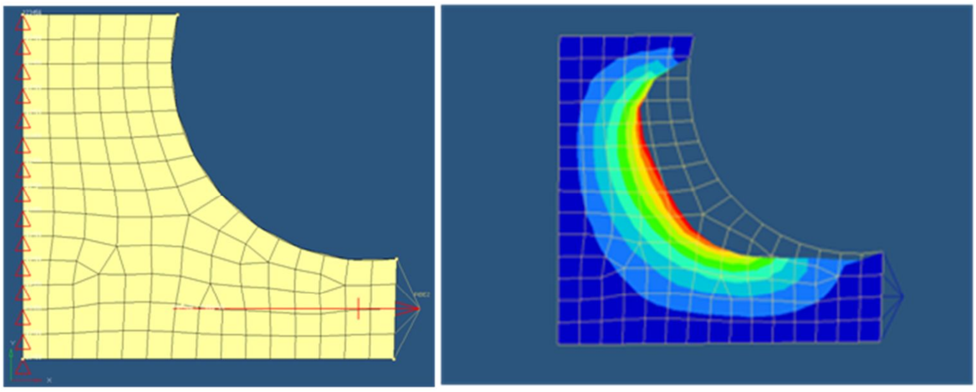


Figure 2 and 3. Freeshape Meshing and Results

Figure 2 shows the results for the modified form after optimization. We can see the original form of the plate in wired.

By analyzing the displacement, one can see that the X displacement increases but remains under 0,1mm and the Y displacement decreases below 0,08mm.

C. Topology Optimization

The variable is the topology of the part. In this kind of optimization, it may have appearance or disappearance of holes, reinforcement or changes in connections between elements. Topology optimization is an appropriate method for the early design phase of a new project because it allows exploring new design concepts for structures.

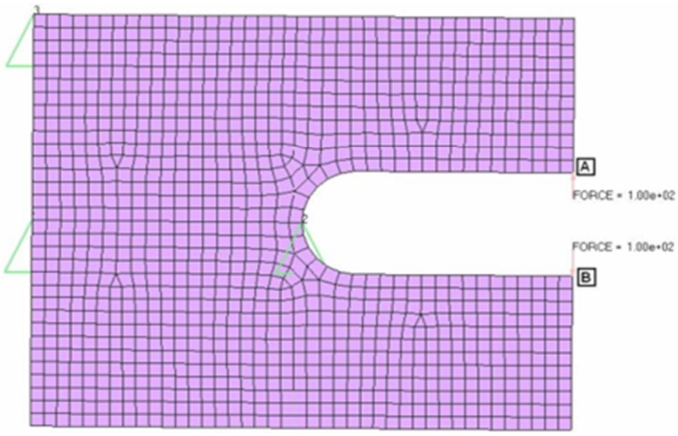


Figure 4. Clip Meshing

As an example of topology optimization, we consider a clip modeled by midplane. The objective of this optimization is to minimize the volume of material.

The problem here is to minimize the volume of the clip with a maximum displacement of 0,07mm allowed in point A and point B. It should be noted that the thickness of the clip remains fixed.

The formulation of the problem is to: *Minimize (Volume)* with displacement constraints:

- Displacement A < 0,07mm
- Displacement B < 0,07mm

At the end of the optimization process, the proposal was obtained as shown in Figure 5. We can see the appearance of holes leading to the reduction of the volume of the clip. The solution is very innovative, compared to solutions proposed by different engineers.

Figure 6 shows the results in displacement. We note that the initial displacement is 0.03 mm and after optimization, it is 0.069 mm.

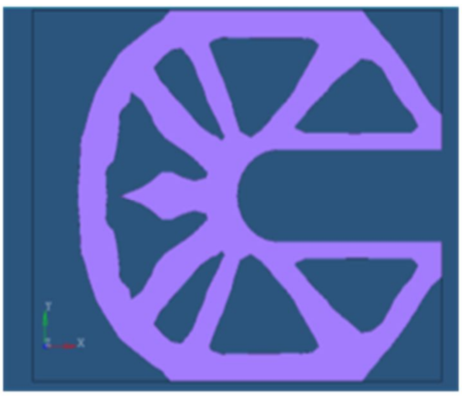


Figure5 clip optimized design

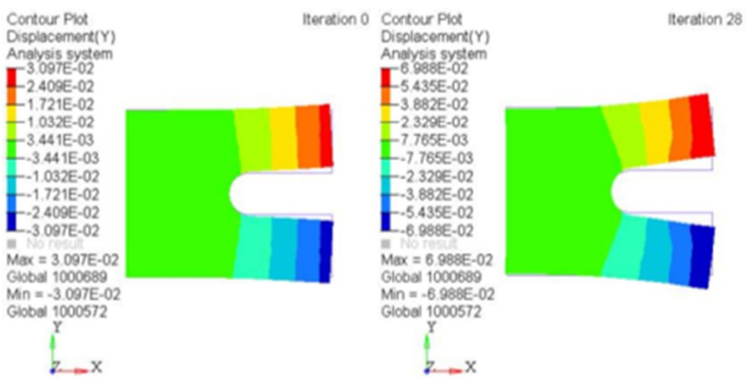


Figure 6 Displacement evolutions

IV. MANAGEMENT OF THE DESIGN PROCESS

After analyzing the specifications to identify various parameters of the part and the optimization problem, three main processes can be defined for optimization [7,8,9].

A. Process 1 : Traditional Design

It is the based on the classical phases of a "manual" approach: design then prototypes and/or simulation. We don't consider this process anymore.

B. Process 2 : Parametric Design

It is based on a parametric design. The operator parameterizes the design by CAD and such parameterization can then be used to define a kind of "design space". This can be economically interesting when the shapes are based on families (due to manufacturing constraints, for example.). Many examples can be found in the literature. In our team, we developed some industrial cases in the automotive domain for instance. The main economical advantages are presented mainly in the early stages of the design process.

An example of the process and the inherent economical gains can be illustrated on an example we developed for Faurecia.

Faurecia society responds to car manufacturers for the design and manufacturing of rear cars tablets. From some elements provided by the customer orders (curves...), the integration in the CAD of trade rules should lead to a dedicated system which automatically builds the tablet. A complete numerical chain allows to simulate the behavior, with the ability to change the model of the tablet.

The following global process can be defined:

- Client specifications (some curves, some constraints …)
- Design modeling, using manually trade rules
- Data definition for simulation
- FEM : using a commercial tool
- Simulation : using an existing commercial software
- Analysis of the results

An integrated solution takes into account step 2 to 5:

- Design modeling: automatic, based on trade rules and templates (CATIA). Giving some parameters, the user gets a model in some minutes. This model respects the defined trade rules.
- Surfaces extraction: considering trade rules and client specification, important functional surfaces are automatically extracted in order to prepare simulation (templates).
- Data definition for simulation : a specific application has been developed (software development).
- FEM: a specific application has been developed (software development). In particular rules and trade knowledge, this leads to a FEM dedicated to the application. It ensures that the simulation software is in the best conditions to calculate.
- Simulation: the data (data + FEM) are automatically linked with an existing commercial software.

From an economical point of view, the results are significant :

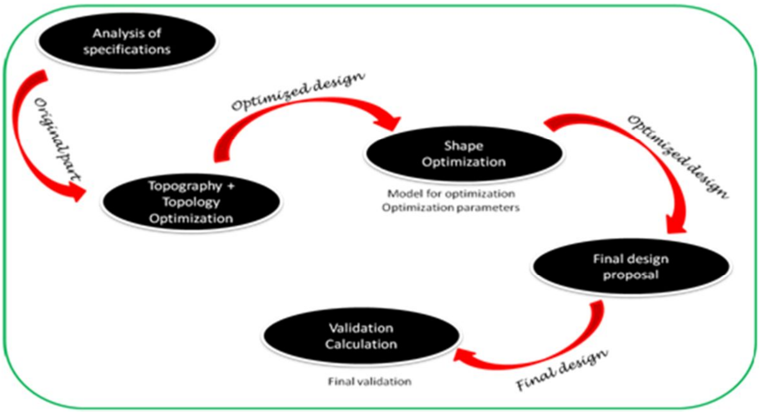
- Quality : it is sure that the trade rules are respected all along the process
- Delay: before this development, the design and simulation of a solution could take one or two days. Using the dedicated application, it is done within some minutes. It is the possible to try alternative solutions.
- Costs: it is possible to try some alternative solutions. It is also easy to try to optimize the cost of the proposal.

Moreover, if the client confirm, nearly all the design is soon developed, which is a huge economical gain.

C. Process 3 : Optimization For Design

It inverses the manual process, putting first optimization phase, which gives a "design space". This design space has to be detailed by the user. This process combines several disciplines of optimization to obtain the results according to the specifications. This process, in general cases, leads to the most important economical gains.

The following are industrial examples using this process.



V. TWO INDUSTRIAL EXAMPLES (PROCESS 3) FROM AN ECONOMICAL AND MANAGEMENT POINT OF VIEW

A. « Lock Interface » [3]

"Lock interface" is a safety component in the assembly of a guide column produced by NPL Company (situated in "Ardennes" and specialized in cutting, stamping and assembly of sheet metal parts). This part is solicited with antagonistic effort in his working. In fact, under certain operating conditions, it must respect some displacement and stress and for a very specific case of extreme load, the "Lock interface" must break in order to protect the user. Figure 10 presents all load cases of the part.

Figure 7. The « Lock Interface »

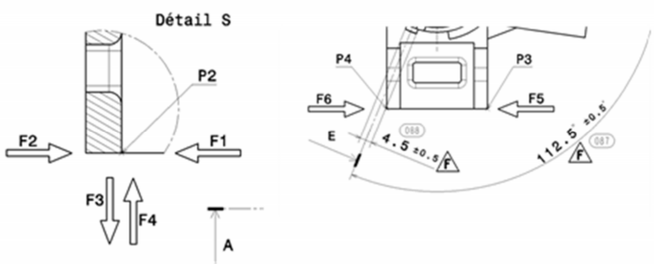


Figure8. Different load cases

In this case, we have coupled topographic and topology optimization. The topographic optimization is used to stiffen the structure of the "Lock interface " to meet the displacement requirements for some load cases.

The topology in this optimization problem, allows us to find the best material distribution in the failure area desired for a specific load case. The input data for these two optimizations are to define areas "design space" and "non design space" and formulate the mathematical optimization problem.

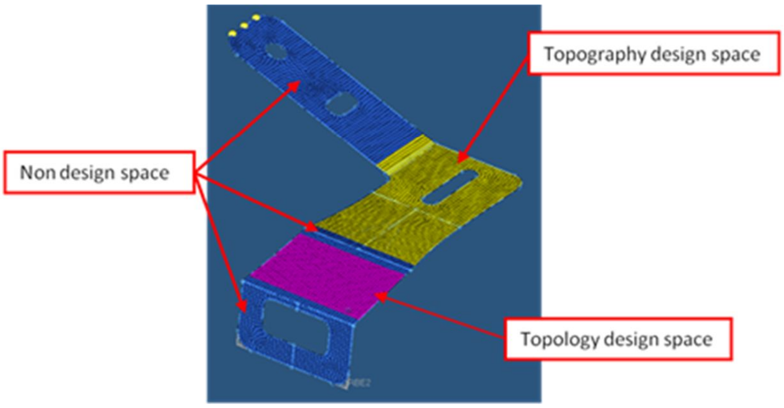
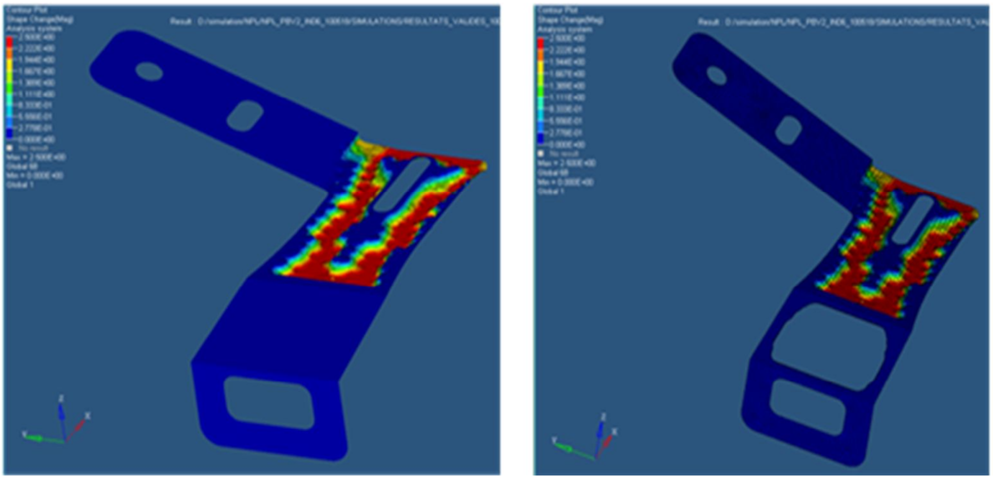


Figure 9. Input data

The results of this topology / topography optimization are shown in Figure 10.

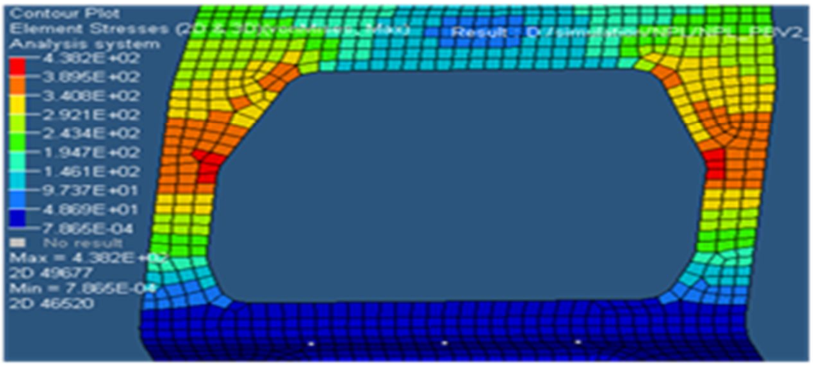


– Free shape optimization

Figure10. Results of coupling topology-topography

The Analysis of the results shows that some areas are over-constrained for load cases. These very high stresses appear in the area of material removal by the topology optimization. A free shape optimization is performed to find an optimal form of material removal in order to reduce stress.

From the optimization result, recovery of a free shape optimization is performed with the objective of reducing the stress constraints. Figure 11 shows the Von Mises stresses obtained after the free shape.



– Interpretation and integration of knowledge

Figure 11. Results of shape optimisation

After the interpretation of the optimizations results, a CAD model was made as presented in Figure 12.

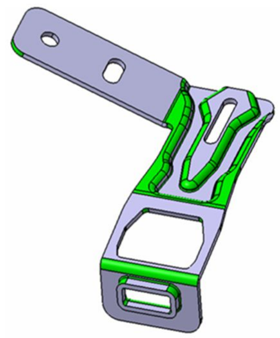


Figure12. CAD modelling from optimization results

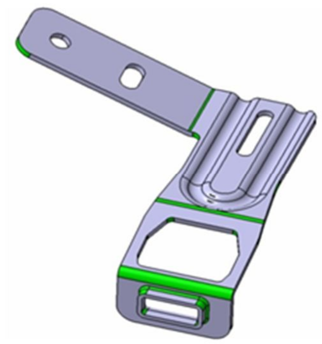


Figure 13. CAD model using trade knowledge

After the analysis of the model and integration of manufacturing parameters (cost of manufacturing tools, tolerances, manufacturing process) for making the “Lock interface”, we need to change the "theoretical". We model a CAD that is more feasible and less expensive (Figure 13). This model is subject to a final validation calculation (Figure 14) to verify the specification.

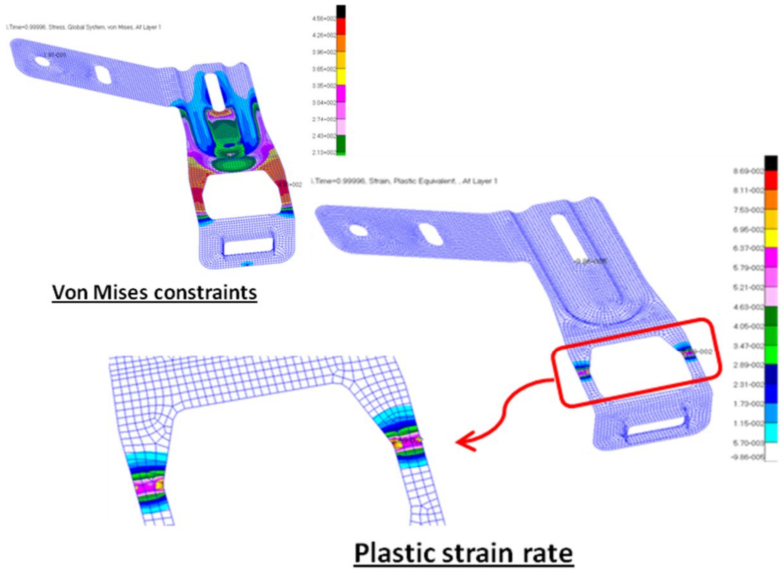


Figure 14 . Validation of the final model

B. Industrial hook

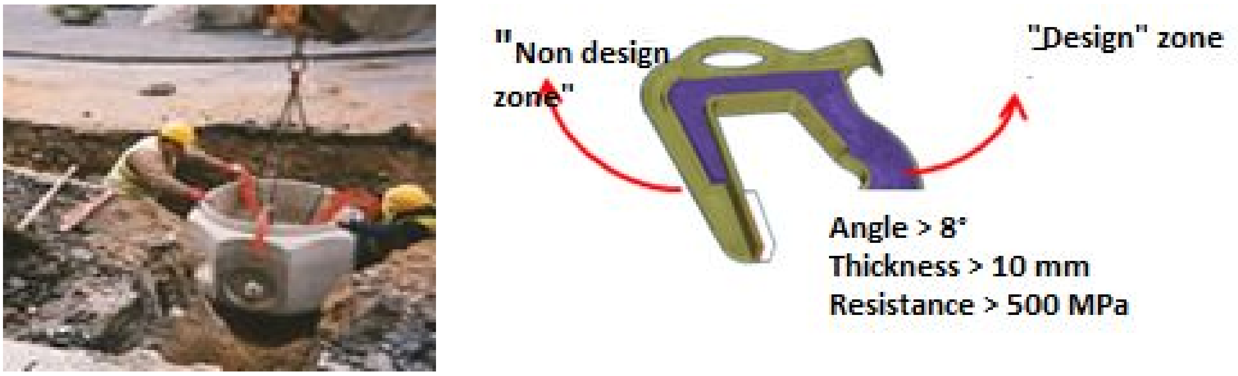


Figure15. the industrial hook

The objective is to optimize an industrial hook for lifting of heavy objects.

A topology optimization is used to minimize the mass of the final product.

By defining two zones (non-design and design).

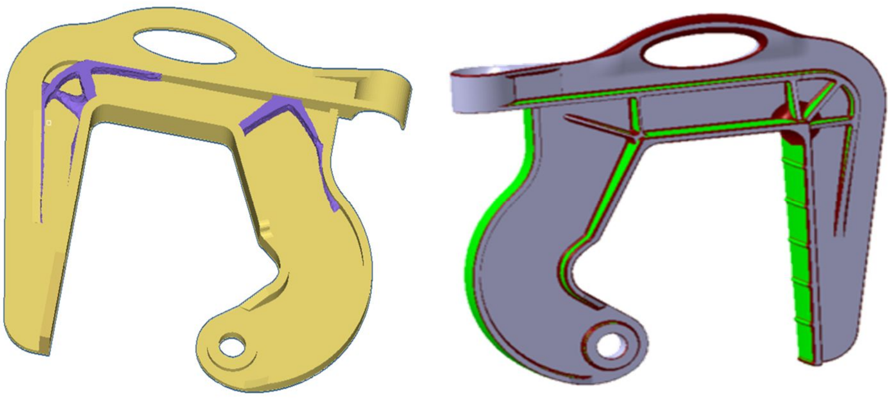


Figure16. design and non design zone

The mass of the final product is minimized (from 8 kg to 5 kg) which is a very important economical gain.

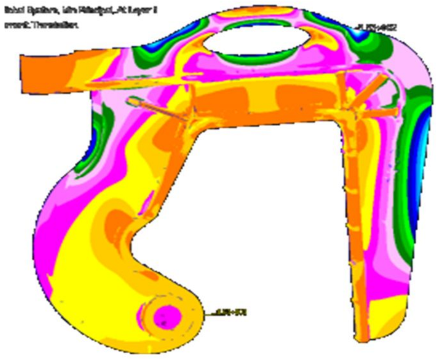


Figure17.Validation of the final model

A final simulation verifies that the innovative form respect the constraints.

Physical tests proved that the new product respects the constraints.

The process leads to a new product which has been manufactured.

VI. CONCLUSION

Nowadays, the design optimization of mechanical structures proves to be of great significance in various industries. To produce more powerful structures at low prices with shorter development time enterprises should abort "try and error" approach and adopt the automatic optimization process by the use of optimization software. The new methods of optimization are made possible through the development of mathematical techniques to solve optimization problems which are briefly presented in this paper. The engineer can scan a large design space by using different formulations in order to obtain optimal solutions of their structures.

In addition, it is important to take into account the entire process (design, manufacturing ...) and to use trade knowledge. In the domain of mechanical structures, many variables have to be processes. Nevertheless, this paper only emphasizes on new solutions to a structure problem during the design phase because it is the best to evaluate different strategies.

With these precautions, the use of optimization, even only in the design phase, can lead to very innovative solutions and thus yield huge gains.

VII. ACKNOWLEDGEMENT

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