INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

INNOVATIVE TEACHING APPROACH FOR THE DESIGN PROCESS OF MECHANICAL PRODUCTS

Antoine VARRET, Morad MAHDJOUB
Université de Technologie de Belfort Montbéliard, France

ABSTRACT

Nowadays, numerical simulation tools take a central place in the design process of mechanical products, to face the imperatives of reducing costs and development time. However, their use is often done for the validation of a solution in the latest stages of a project, even if they are more efficient earlier in the project for the help to find solutions. Statistical and optimization tools, in an approach based on designs of experiments and response surfaces methodologies, could be an important help, associated with numerical simulations, to find new product architectures. Nevertheless, their use is commonly reserved for complex problems with costly simulations. This article presents a design methodology based on numerical simulation and optimization tools to help to find original optimal architectures. The results of the experimentation of this design process on student projects are presented.

Keywords: engineering education, numerical simulations, optimization, response surface methodologies

Contact:
Antoine Varret
Université de Technologie de Belfort Montbéliard
IRTES - SET
BELFORT CEDEX
90010
France
antoine.varret@utbm.fr

1 INTRODUCTION

Engineering schools aim to deliver a high level practical training. Acquisition of technical knowledge in traditional lectures, tutorials and practical work is essential, but these learning methodologies are often criticised. Students are too passive (Abersek and Popov 2004) and they have difficulty to putting into practice this theoretical knowledge. The use of active pedagogies to complete this training, is a good way for students to take over a significant portion of the responsibility for their own learning (McCowan and Knapper 2002). For mechanical engineering schools, a central objective is to train students in the design process of mechanical products. Admitting that 75% of the product costs are fixed by the decisions taken in the first stages of the design process (Perrin 2001), the challenge is to help students to find original solutions to technical problems, while following a rigorous and effective succession of phases.

Regarding the design process of mechanical products, the necessities of reducing costs and development time have contributed to the decrease of experiments and tests on prototypes, and to the development of numerical simulation tools. The latter are widely developed to now take a central place in the design process, which are as useful for helping this design process, as they are for the validation. Nevertheless, they are paradoxical, because of their need to rely on a CAD model. In the first stages of the design process, the improvement potential of a solution and the room for manoeuvre are high, but the context is fuzzy, and it is difficult to have a well-defined model. Later, when a model is defined, simulation tools can be used with relative ease, but possible modifications are more limited. If a major sizing mistake is detected, it is already too late for the process to be efficient.

This paradox is the same for optimisation tools, coupled with simulation tools, which are more easily used in the later stages of the design process, when the improvement potential of the product is limited. There is a strategic challenge to use these tools in the first stages of the design project, for strong power of improvement.

This paper proposes to illustrate an innovative active learning methodology concerning an efficient engineering process of optimised products, by introducing, as soon as possible, numerical simulation tools and optimisation tools in the design process. The methodology is tested within an engineering students' project.

2 STATE OF THE ART AND RESEARCH OBJECTIVES

2.1 Numerical simulations and engineering process

Numerical simulation aims to check as soon as possible that the products have the characteristics required to meet the functional specifications they correspond to. It operates both upstream and downstream of the design process. Upstream is used to help the designer in selecting an architecture, in an approach called "CAE centred" (Computer Aided Engineering). This one manipulates simplified and easily scalable models, designed to meet the needs of the simulation. Downstream is used to validate the final solution, in an approach called "CAD centred" (Computer Aided Design). This is to ensure that the final geometry guarantees the performance specified in the functional specifications (Devalan 2009). Among these two approaches, although the CAE-centred approach is the most natural and does not have the implementation problems of the CAD-centred approach, it is the latter which is mostly used by organisations (Lee 2005) (Lafon 2007). This is not unproblematic, since the numerical model, which has an excessive level of detail in relation to simulation needs, requires a previous step of simplification, which increases the computation time and is not easily scalable. However, the evaluation of product performance occurs late in the design process, resulting in dysfunctions and associated loss of time (Helms 2002) (Lonchampt 2004). The preliminary design phase is not treated according to the level of importance that it requires, because of a lack of appropriate tools (Yannou 2001).

The CAE-centred approaches are close to SBD methodologies (Simulation Based Design), which include design methodologies for which the simulation is the primary means of evaluation and validation of the design (Shephard and al. 2004). This is explained by the fact that it is a powerful visual tool which improves our understanding of the behaviour of the product (Lehtonen 2006). However, the SBD faces limitations such as the inability of numerical simulation tools to indicate areas for improvement of this behaviour, and especially when the simulated phenomena are complex.

Furthermore, the manipulation of multiple variables, which often involves interactions is difficult. This relates to the field of optimisation (Aittokoski 2007).

2.2 Optimisation and engineering process

The optimisation is primarily a tool of decision help, the choice of a solution rather than another belonging to the designer (Grabener and Berro 2008). However, if optimisation is present in many companies, solving a problem of mechanical optimisation is carried out most often following a trial and error approach (Roy and al. 2008) (Caliskan and Uçar 2011). This type of research builds on the skills and experience of the designer and often uses numerical simulations. This is a slow process, characterised by a limited number of analysed solutions. The optimisation takes time, and the improvement potential is low.

The multi-objective optimisation of complex systems that implement costly simulations typically follows another solving approach, based on DOEs (Designs Of Experiments). This approach allows to assess the level of influence of each parameter on the constraints and objective functions, and thus to gradually reduce the search space to the most interesting areas. Optimisation algorithms, stochastic or deterministic, are inadequate for complex problems, due to the calculation time, which limits the number of possible iterations, and the constraints and objective functions, characterised by the presence of many local optima (Song and al. 2008). For these kind of problems, the systematic use of the simulator is illusory and the best approach is to replace the objective functions from the simulator by simple statistical models (the response surfaces) representing, at best, these functions (Jourdan 2005). The interest of the construction of these models is to perform an algorithmic optimisation without appealing to numerical simulations, the function values being extracted from the response surfaces. Optimal solutions chosen must then be checked by numerical simulations. According to Troussier (Troussier 2010), the coupling of phenomenological models (based on physical behaviour), and statistical models, represents a strategic interest for the development of simple models, allowing a fast simulation of their performances, which is sought in the preliminary design phase.

2.3 Teaching approach of Optimisation in the engineering process

According to Hailey and al (2005) and Hill (2006), simulation tools are of crucial importance, and their integration into higher technical education is essential as a tool for decision support, allowing to evaluate a set of alternatives and to lead to an optimal solution. Generally, the mastery of these tools, as well as optimisation tools would avoid conventional trial and error approaches. This point of view is shared by Lee & Lee (2005), who think training to CAx systems is strategic: today the use of such systems grows in companies in order to reduce costs and delays. However, according to Dankwort and al (2004), in the fields of CAx, universities suffer from a broad but superficial formation. Moreover, students should not only be trained in CAD modelling, but also in all aspects of computer-aided product creation.

Another shortcoming generally observed in the training of engineers is that they suffer from teaching where students are too passive (Abersek and Popov 2004). According to Duderstadt, ‘‘Today’s engineering students have all too little opportunity for discovery-orientated, interactive, and collaborative learning experiences’’ (Duderstadt 2008, p. 33). Active learning is nevertheless a highly effective way to develop professional skills, initiative, and to integrate the different sources of knowledge (McCowan and Knapper 2002). Some universities adopt such initiatives, and we can include, without being exhaustive, the work of Abersek (2004), Carmen (2012), Dankworth (2004), Liebenberg (2012). However, the methodology we propose in the next section seems to be unique and original today.

2.4 Issues raised and objectives of our research works

In view of the state of the art, we can see that the design process of mechanical products, implementing numerical simulations, has a number of shortcomings and dysfunctions:

- the evaluation of the product is late,
- the use of simulation tools arrives late in the process, and they are mostly used as a validation tool and not as a tool for decision support,
- the optimisation step, combined with numerical simulations, is present in most processes, but it is often done manually. Algorithmic optimisation is rarely used, and optimisation based on DOEs is reserved for complex systems which need costly simulations.

The objective of our work is first pedagogical and has two aspects:

- We propose an active pedagogic methodology of mechanical products design which includes a pre-dimensioning stage. The concrete subjects proposed allow students to put into practice their theoretical knowledge on practical cases. Mechanical products developed need knowledge from the structural mechanics field: static, dynamic, fatigue, dimensioning of structures and links.
- The embodiment-design stage includes the use of simulation and optimisation tools, to help students for the product architecture design. We want them to acquire reflexes that will enable them to avoid the pitfalls of the design process cited above.

3 PROPOSED MODEL

As said before, our methodology is applied to design from scratch for mechanical products, subject to various types of stress, primarily within the field of structural mechanics.

We refer to the Pahl and Beitz (1996) description of the design process, widely recognised by the scientific community, and illustrated in figure 1 below. Concerning this process, our goal is to improve the performance of upstream phases, by inserting, as early as possible, a pre-dimensioning phase using numerical simulations and optimisation tools. That is why we propose to introduce these tools at step 3. Our contribution is to provide to the designer several statistical and algorithmic tools coupled with numerical simulation tools. It is also to formalise the implementation of these tools in order to help the identification of original architectures. Our goal is to allow the designer to quickly evaluate various geometries and easily introduce major changes. We want to improve the design process performance, and avoid the risk of selection of a solution containing major errors of sizing.

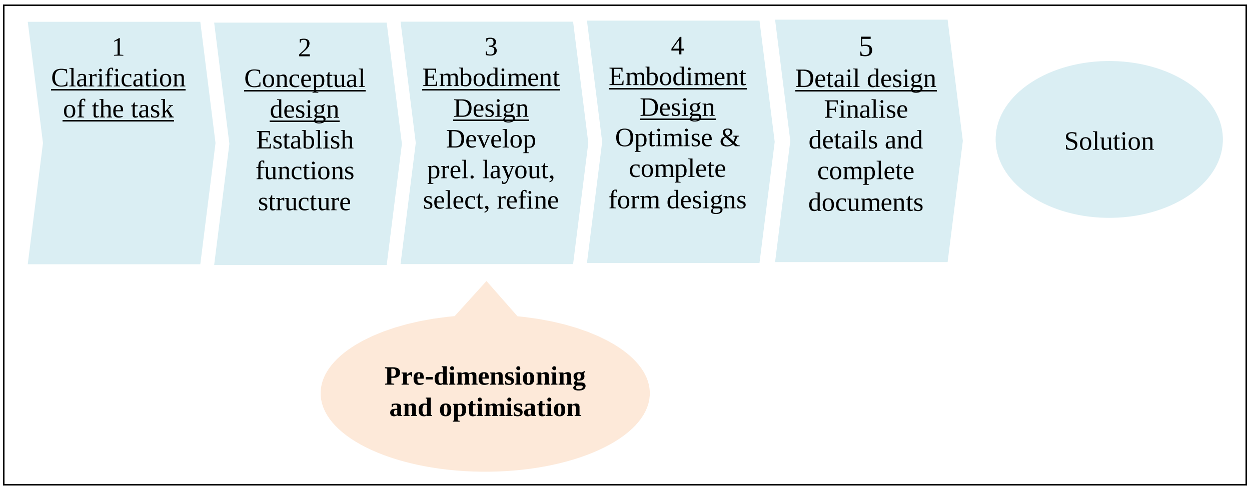

Figure 1.model of the design process (from Pahl and Beitz 1996), and our contribution.

Consequently, step 3 contains two phases:

First, theoretical pre-dimensioning calculations are done. These calculations belong mainly to the solid mechanics and strength of materials: calculations of bearings, gear teeth, spring sizing, sections of trees, choice of standard components on catalogues (bearings, gears, seals, keys...).

Then comes the pre-architectural design phase. The help of numerical simulation and optimisation tools leads to an architecture which is a good compromise between the different objectives of the project. This phase begins by the CAD modelling of functional surfaces corresponding to the inter-element linkages, and the application points of stresses, followed by development of the geometries between these surfaces and forming the product architecture. The initial geometries subject to a simulation are very basic, and represent the maximum dimensions of parts. Following this first simulation, an iterative process of removing material and simulation is carried out until a geometric entity with a uniform distribution of stresses is obtained. Parameterisation is then fulfilled with the view to optimising the model. A suitable model for optimisation is characterised by an almost homogeneous distribution of stresses, and geometric parameters affecting this stress distribution. It is particularly important that the parameters can affect areas of stress concentrations. Optimisation is then achieved by coupling between the parametric model, the optimisation tools and the finite element solver. The resolution utilises methodologies based on DOEs, response surfaces and stochastic algorithms in a sequence shown in figure 2.

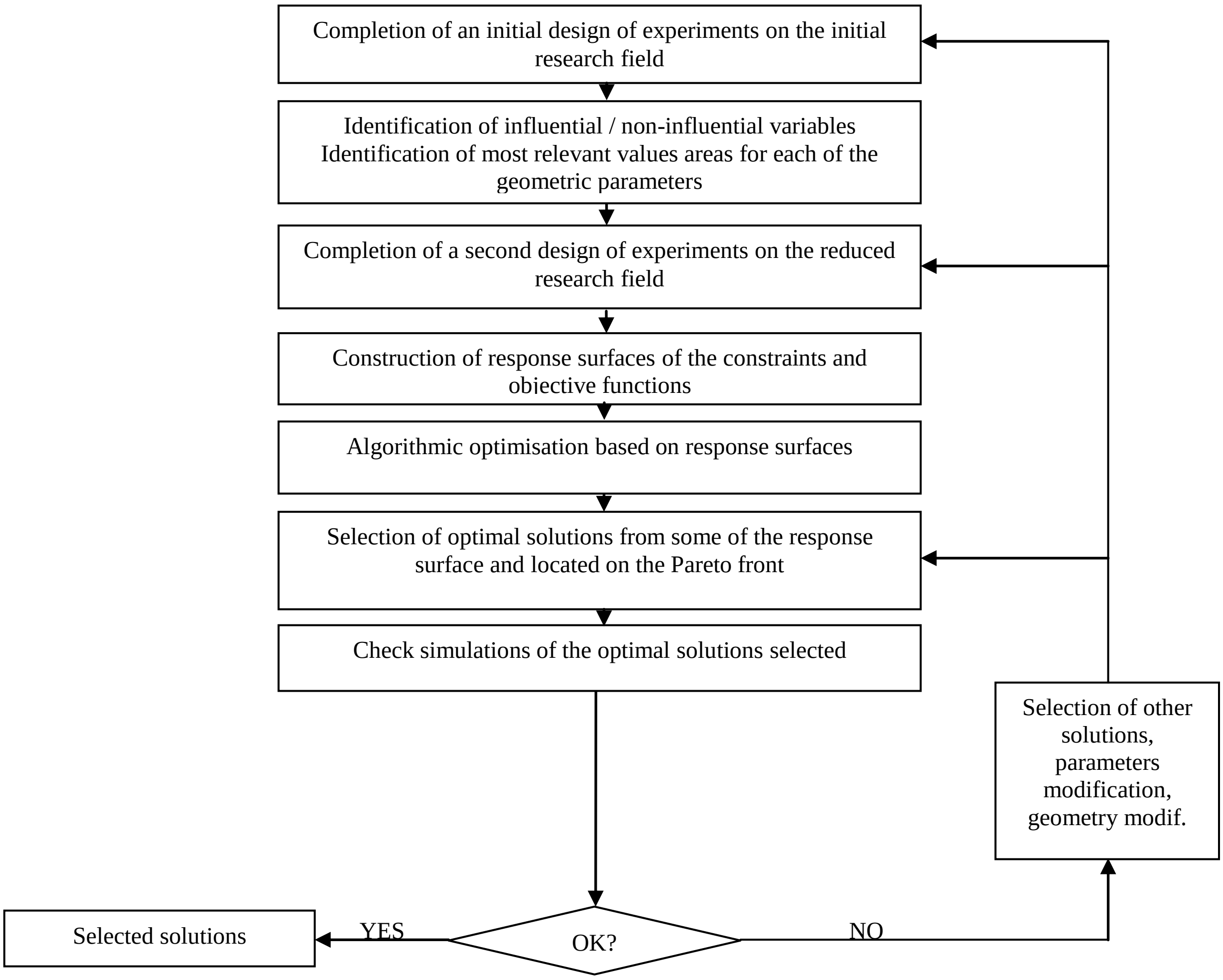

Figure 2 :Steps of the geometry optimisation process.

Our aim is to combine the interests of statistical tools to identify ways to improve the architecture (identification of influential variables and their effect, proportional or inversely proportional) in the architectural research phase. The architecture outlines being drawn, the optimisation step based on response surfaces and stochastic algorithms allows us to improve rapidly and noticeably the solution performances by identifying the optimal configurations of our parameter sets.

4 EXPERIMENTATION

We experimented with our methodology in a course relating to the design and dimensioning of mechanical systems, over a 12 week period. This course is organised as follows: a 1 hour lecture and 4 hours tutorial per week.

The lecture is used to give instructions for the successive stages of the project and reminders on the technical subjects usually encountered in the projects. For example, the lectures talk about the different following subjects:

- External and internal functional analysis
- Which criteria for the dimensioning?
- Structural optimisation: the successive steps
- Output of the installations
- Rules for the CAD model development
- From the functional requirements to the technical specifications…

The tutorial is used to make weekly points on the different projects. Knowing that a tutor group contains up to 30 students, and that a minimum of 20 to 30 minutes is necessary to review each project, a tutorial group has up to 8 to 9 groups of 3 to 4 students, each working on a different subject. Students are male and female (15% to 20% female), 21 to 23 years old, from an engineering degree (this course aims at synthesising theoretical knowledge learned during the first two years of the engineering school). Subjects are proposed by the teacher, or by the students if they are considered suitable relating to the course objectives. Here are, for example, industrial or academic subjects of the two latest courses:

- Innovative propulsion mechanism for paddle boat (academic)
- Recumbent tandem (academic)
- Stirling engine (academic)
- Manual rolling machine for spring manufacturing (academic)
- Brake for skate (industrial)
- Boost for scooter (industrial)

The course plan is organised to allow students to carry out the entire process, from the description of the need up to the drafting of “good for manufacturing" documents. The schedule is illustrated in figure 3 below:

<table>
<tr><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W5</th><th>W6</th><th>W7</th><th>W8</th><th>W9</th><th>W10</th><th>W11</th><th>W12</th></tr>
<tr><td colspan="2">Step1
Clarify the task</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="3">Step 2
Conceptual design</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="5">Step 3
Embodiment design, preliminary layout
Pre-dimensioning and optimisation</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="6">Step 4
Embodiment design, completion of CAD model</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Step 5
Finalise the definition,
final parts lists and plans</td></tr>
</table>

Figure 3: Project schedule.

As reminder, these steps follow the Pahl and Beitz design process model, our contribution being in the introduction of simulation and optimisation tools at the embodiment design stage. Figure 3 shows an overlapping of successive stages. We cannot speak of a real process of concurrent design, because there are no manufacturing actors in the project groups. Therefore, students had to take into account the manufacturing constraints for their products, and the overlapping of the successive stages was done by the fact that groups had to start a new step before the end of the previous one.

An important last point for the success of this course is to place milestones at the end of each step, with homework to return, and timely feedback from the teacher. This is a major point to make the students work in an intensive and effective way. This latest point is another reason why the number of projects followed by the teacher must stay reduced.

Among the proposed projects, the recumbent tandem was followed by two students. The results of this project are presented in the following paragraph.

5 RESULTS

In this project, the students were responsible for the design of a fully suspended recumbent tandem, for which the two seats can be fully adjustable to accommodate people whose size varies between the 5th female percentile and the 95th male percentile. The following paragraphs present the results of the different stages.

5.1 Clarification of the task and functional design

Students began with ergonomic research on semi-recumbent postures for a good compromise between performance and comfort of the pedalling station. The use of the CAD mannequin helped to identify ergonomic postures, the visual field of the passenger and the size of the product for the postures adopted (Figure 4). The analysis of existing similar products was then carried out, as well as the generation and prioritisation of several pre-concepts. The pre-concept selected is shown Figure 4.

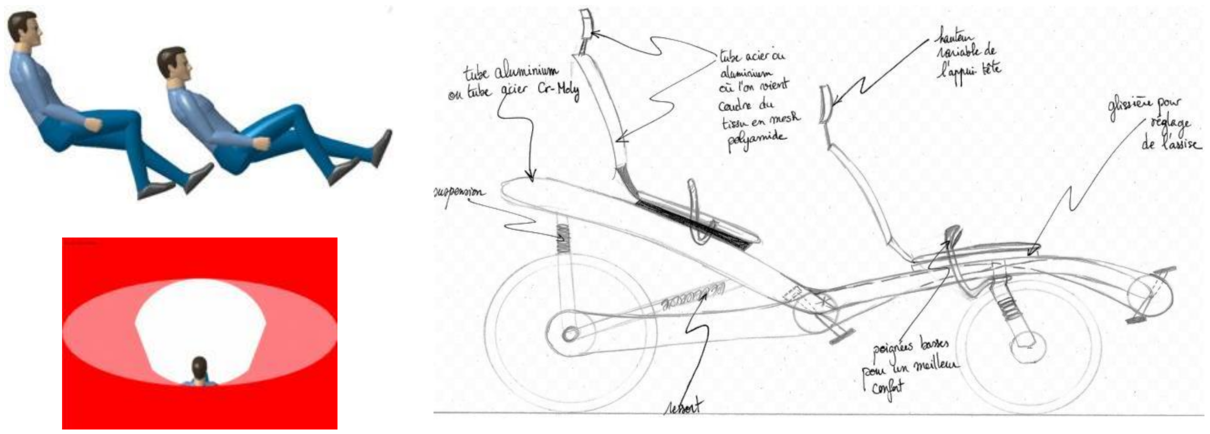

Figure 4:Postural ergonomic analysis and illustration of the passenger field of view (left). Pre-concept selected (right).

5.3 Architectural research

This phase has followed the proposed process: First, the exploration of various architectures was helped by the numerical simulations (Figure 5).The goal was to identify with an as homogeneous as possible distribution of stresses.

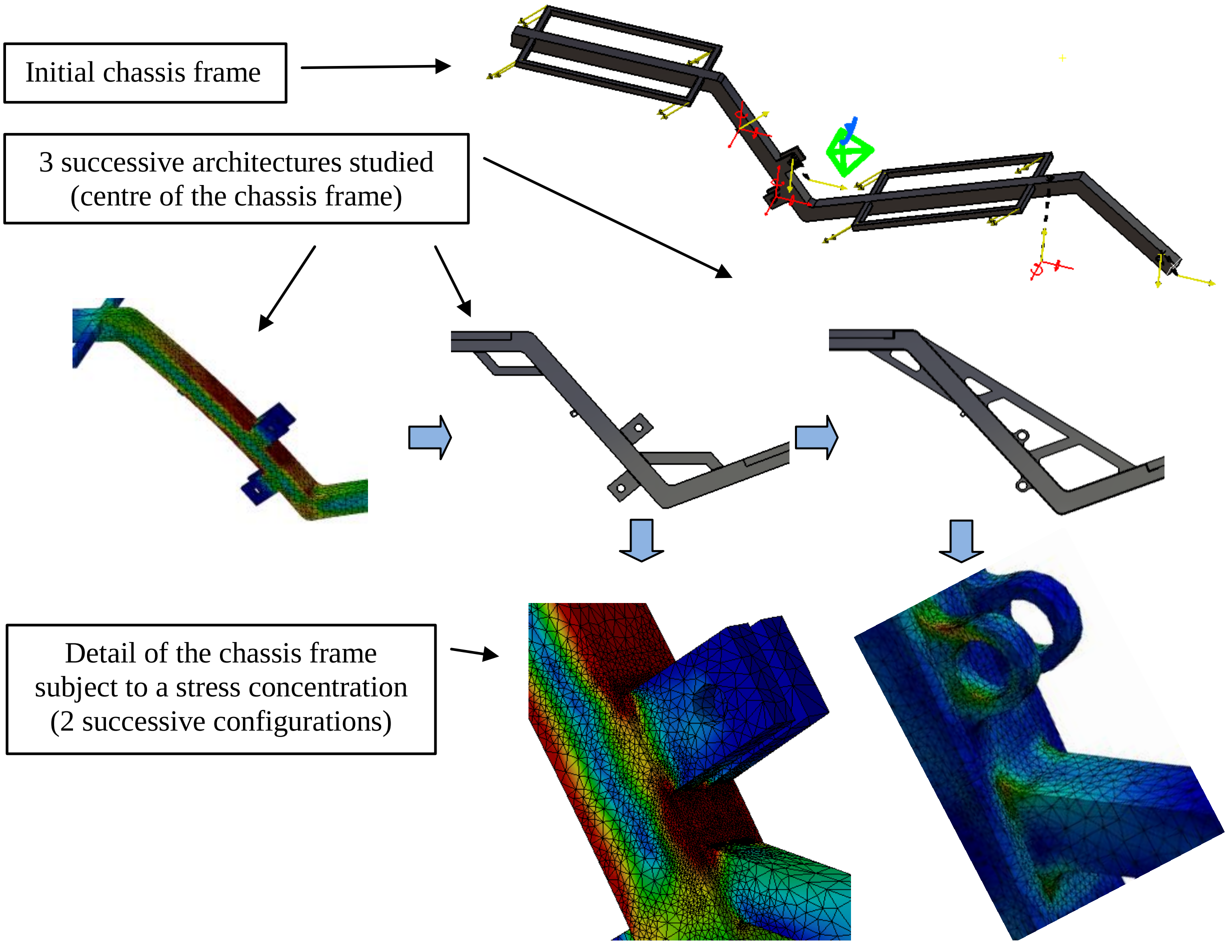

Figure 5: initial geometry and steps of the architectural research

Secondly, after having identified a suitable architecture, the optimisation was achieved following the process detailed in figure 2, with an algorithmic optimisation based on response surfaces, illustrated in figure 6. The optimisation problem contained two minimisation objectives (the mass and the displacements of the structure subjected to a static load case) and one constraint (the maximum stress, under a maximum value linked to the material used). The initial research space was made of seven geometrical parameters (thickness, height and width of the chassis frame and reinforcements, dimensions of the fillets). Two following DOEs allowed the research space reduction, while keeping only the two most significant parameters (height and thickness of the chassis frame).

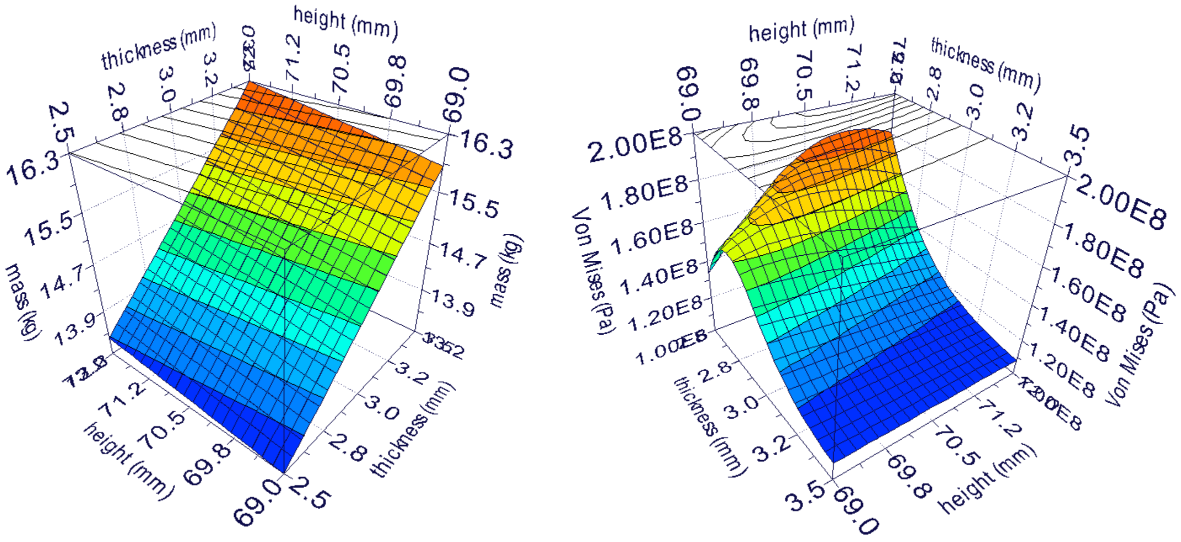

Figure 6: algorithmic optimisation based on response surfaces.

Response surfaces of the mass (left) and maximum stress in the structure (right).

The optimisation process allowed the identification of an optimal architecture with a mass of 10 kg, corresponding to a 30% decrease in comparison with the initial chassis frame.

5.4 Product detailed design

The last step, with the final definition of the product, led to the detailed CAD model of the product, drafts and parts lists (see figure 7).

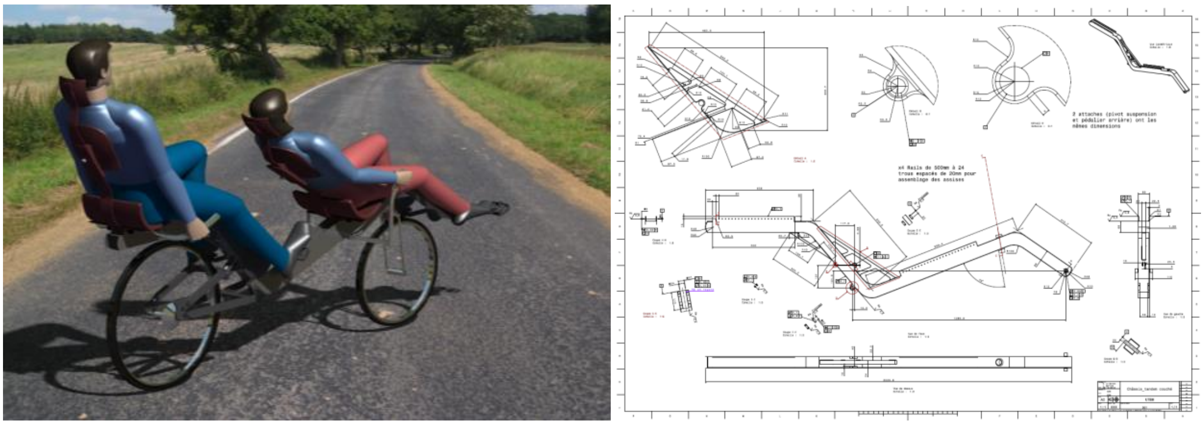

Figure 7: detailed CAD model of the product and draft of the chassis frame.

This figure shows the results obtained by the students at the end of the course. The next step, beyond this course, is to manufacture a prototype with the means of the school workshop. This is possible because the students developed their product taking into account the manufacturing process of our workshop (milling and turning of metals, folding, cutting, bending and welding of tubes and sheet metal parts) and achieved the detailed definition of the product, including manufacturing drafts and part lists.

6 CONCLUSION

In this article, we showed an innovative teaching approach of the mechanical products design process. This methodology allows students to carry out a complete design process of new products in an active pedagogic approach. It allows also to evaluate and improve the product performances early in the project, and to reduce dysfunctions and corrective actions in the last stages of the process. We can see that the assessment of the product starts at the beginning of the embodiment design phase, and architectures with important mistakes are avoided. Simulation and optimisation tools are used sooner in the project, and the optimisation process is carried out when major modifications of the geometry are still possible, which increases its improvement potential. These tools help the student to identify efficiently an optimal solution. For the project illustrated in section five (the recumbent tandem), they allowed a significant decrease of the mass (-30%) in comparison with the initial architecture.

We consider this first example, presented section 6, as well as the other projects proposed, as a successful testing of our methodology. Another positive point about this relatively new course (2 courses delivered in autumn 2012 and spring 2013) is the number of students registered: 16 for the 1st course and 30 for the 2nd course, showing a growing interest of the students.

We are conscious that these points do not constitute an evaluation of this methodology and that we have to organise a comparative approach to evaluate its contribution, from the point of view of the efficiency of the design process, and from the pedagogical point of view.

Therefore, this contribution has to be evaluated according to the 2 following lines:

- Efficiency of this methodology compared with a more traditional design process. We identify our contribution in the introduction of simulation and optimisation tools in the 3rd stage of the Pahl and Beitz design model. This contribution would be evaluated by comparison between projects with or without the use of the tools at this stage.
- Pedagogical efficiency of our course: we plan to evaluate the students' ability to use their technical knowledge earned in previous courses, at the beginning and at the end of the project.

These points are our perspectives of future works in the research domains of design education and engineering design efficiency.

REFERENCES

Abersek B., Popov V. (2004) Intelligent tutoring system for training in design and manufacturing. *Advances in Engineering Software*, volume 35, pages 461–471.

Aittokoski T.(2007) On optimization of simulation based design. Thesis Report. University of Jyväskylä, 113 pages.

Caliskan M., Uçar V. (2011) Structural optimization with CADO method for a three-dimensional sheet-metal vehicle body. *Computers in Industry*, volume 62, pages 78–85.

Carmen C. (2012) Integration of a NASA faculty fellowship project within an undergraduate engineering capstone design class. *ActaAstronautica*. Volume 80, pages 141–153.

Dankwort C. W., Weidlich R., Guenther B., Blaurock J. E. (2004) Engineers' CAx education—it's not only CAD. *Computer-Aided Design*, Volume 36, pages 1439–1450.

Devalan P. (2009) Simulation numérique dans le processus de conception de systèmes mécaniques. *Techniques de l'Ingénieur*.

Duderstadt J. J. (2008) Engineering for a changing world: A roadmap to the future of engineering practice. The Millennium Project, The University of Michigan.

GrabenerT., Berro A. (2008) Optimisation multi-objectif discrète par propagation de contraintes. 4th JFPC (Journées Francophones de Programmation par Contraintes), Nantes, France.

Hailey C., Erekson T., Becker K.H., Thomas M. (2005) National center for engineering and technology education. *Technology Teacher*, Volume 64, Pages 23-26.

Helms R.W. (2002) Product Data Management as an enabler for concurrent engineering. Thesis Report. Eindhoven University of Technology, 188 pages.

Hill R.B. (2006) New Perspectives: Technology Teacher Education and Engineering Design. *Journal of Industrial Teacher Education*, Volume 43.

Jourdan A. (2005) Planification d'expériences numériques. *Modulad*, Volume 33, Pages 63-73.

LafonP. (2007) Dimensionnement et optimisation en mécanique : application à la conception intégrée des systèmes mécaniques, aux procédés et aux structures. PhD, Université de Technologie de Troyes, 217 pages.

Lee S.H. (2005) A CAD–CAE integration approach using feature-based multi-resolution and multi-abstraction modelling techniques. *Computer-Aided Design*, Volume 37, Issue 9, Pages 941-955.

Lee K.S., Lee S.H. (2005) Network Based Engineering Design Education. Proceedings of the 9th international conference on Knowledge-Based Intelligent Information and Engineering Systems - Volume Part I, pages 48-55.

Lehtonen M. (2006) Simulation-based design process of smart machines. Espoo 2006. VTT Tiedotteita. Research Notes 2349. 184 pages.
Lonchampt P. (2004) Co-évolution et processus de conception intégrée de produits : modèle et support de l'activité de conception. Thesis report, INPG (Insitut National Polytechnique de Grenoble, France), 233 pages.
Liebenberg L., Mathews E.H. (2012) Integrating innovation skills in an introductory engineering design-build course. *International Journal of Technology and Design Education.*Volume 22, pages 93-113.
McCowan J.D., Knapper C.K. (2002) An Integrated and Comprehensive Approach to Engineering Curricula, Part One: Objectives and General Approach. *International Journal of Engineering Education*. Volume 18, Number 6, pages 633-637.
Pahl G., Beitz W., Schulz H.-J., Jarecki U. (1996) Engineering design, a systematic approach. Third edition, Springer.
Perrin J. (2001) Concevoir l'innovation industrielle. Méthodologie de conception de l'innovation. CNRS (Centre National de la Recherche Scientifique, France) Editions.
Roy R., Hinduja S., Teti R. (2008) Recent advances in engineering design optimization: Challenges and future trends. *CIRP Annals - Manufacturing Technology*, Volume 57, pages 697–715.
Shephard M.S., Beall M.W., O'Bara R.M., Webster B.E. (2004) Toward simulation-based design". *Finite Elements in Analysis and Design*, Volume 40, Issue 12, Pages 1575-1598.
Song G.H., Wu Y., Li C.X. (2008) Engineering Design Optimization Based on Intelligent Response Surface Methodology. *Journal of Shanghai Jiaotong University* (Science), Volume 13, pages 285-290.
Troussier N. (2010) De la conception mécanique à la conception collaborative et robuste des systèmes mécatroniques : une approche combinant maîtrise des performances des systèmes techniques et gestion des connaissances. PhD, Université de Technologie de Compiègne, 177 pages.
Yannou, B. (2001). Préconception de Produits. PhD, ECP (Ecole Centrale de Paris), 184 pages.