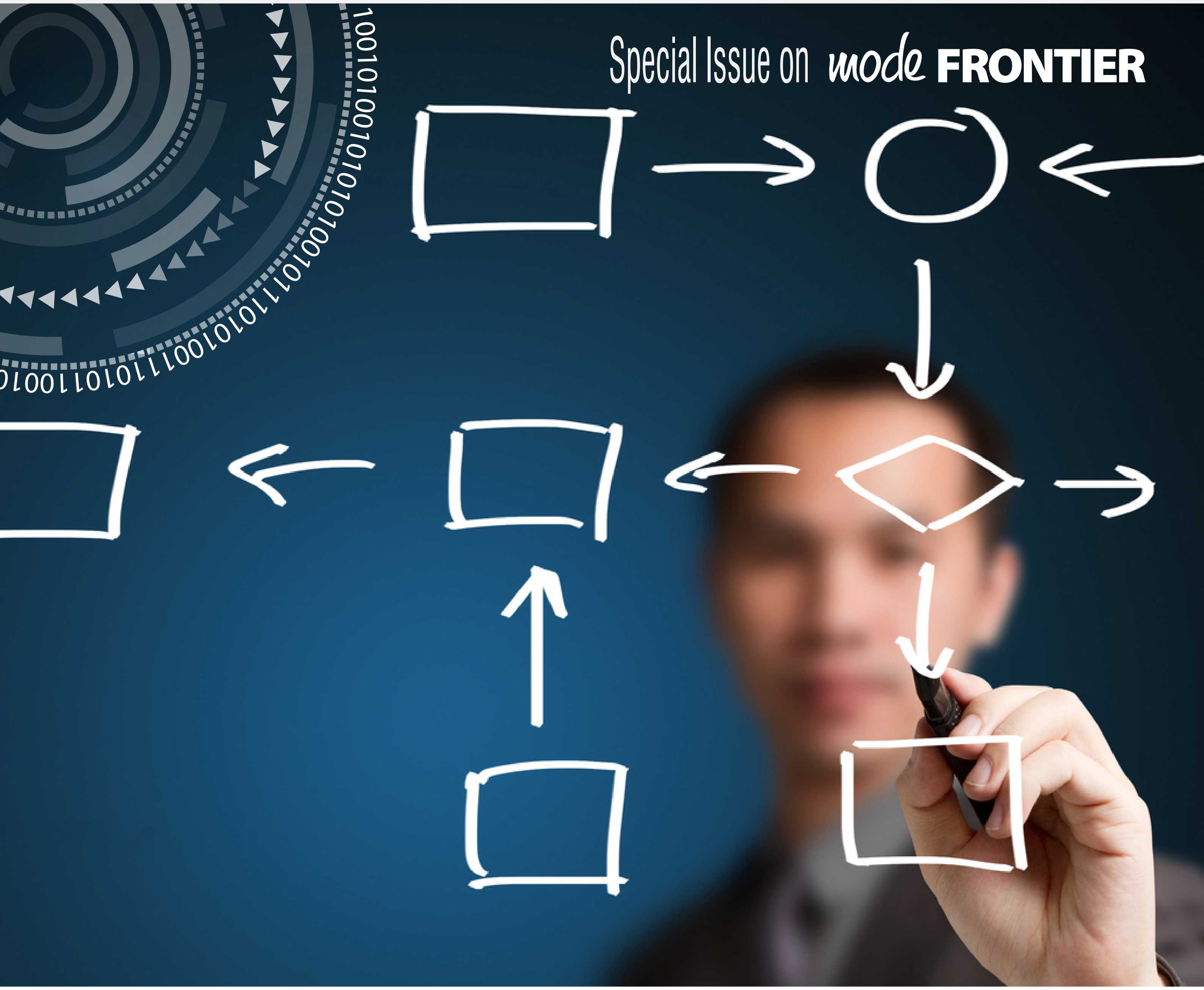
Newsletter

Simulation Based Engineering & Sciences



Multi-Objective Optimization of **Vehicle Handling & Comfort** Performances

Structural Optimization of a Car-body **High Speed Train:** an innovative analysis

Robust Design Optimization of a **Bumper System**

Mechanical optimization of the injection system in a **compression molding machine**

Parametric FEM model optimization for a **pyrolitic oven**

Pioneers in numerical optimization solutions

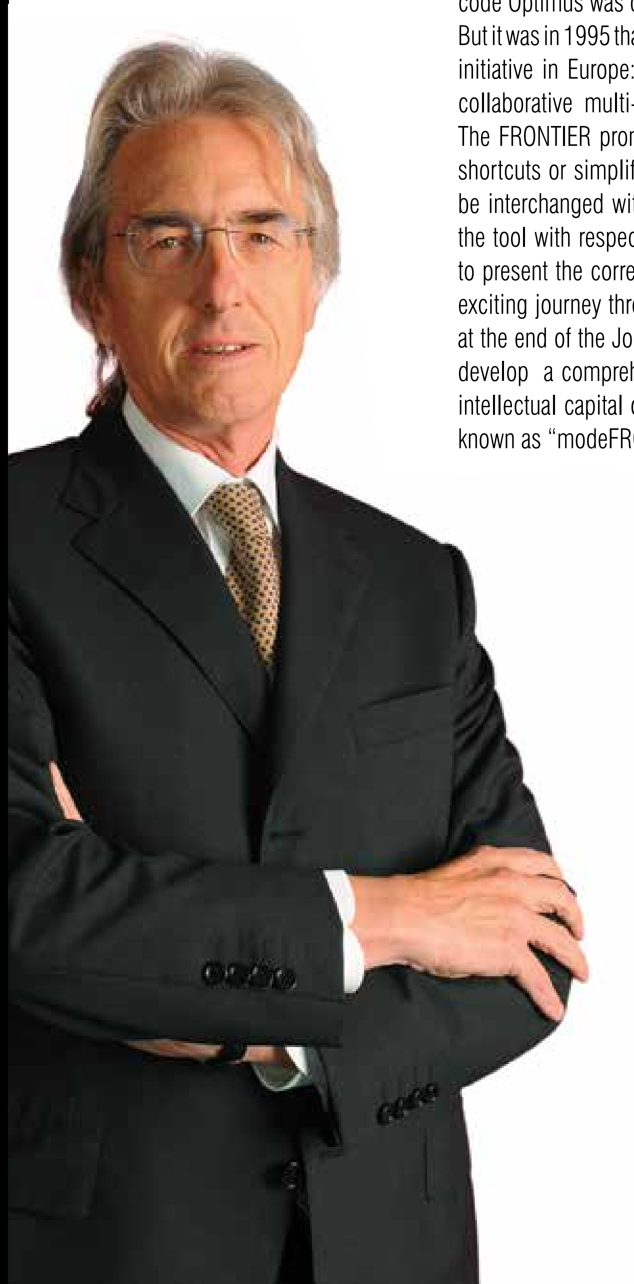
modeFRONTIER
and the EnginSoft Newsletter Special Issue

In a variety of industrial contexts, engineering simulation is recognized today as the most powerful enabler of new product development, since a very fast virtual design and development process leads to an unparalleled rate of learning of the products which have to be manufactured. This fact is no longer in doubt. However, why not have on top of the different engineering simulation technologies, or even and directly on top of the design process itself, a software system reflecting the logistics of the design process, and performing - in a sophisticated and integrated manner - an automated search on the design space targeted to identify the optimal solutions, whilst simultaneously capturing the embedded know-how?

The engineers at EnginSoft have been consumed by this aspect and the value of engineering simulation since the very beginning of our activity, some 40 years ago. Looking back to those very pioneering times, I can mention the work presented at the "First International Conference on Engineering Software for microcomputers" (1984), where we suggested automated solutions to minimize the overall weight of lightweight steel roofing, or the book that we were commissioned by HP ("Civil Engineering – Volume 5", 1986), which was entirely dealing with automated optimization of special structures, including pre-stressed concrete members, built-up welded beams, shallow foundations, and the like. Following on from this, we were deeply involved in the challenges of p-element super-convergence and corresponding parameter-based optimization. The developments in this area, including many industry-related implementations, led to a conference on "Industrial Reality and Design Optimization", which was organized by EnginSoft in 1994.

Meanwhile we always had an eye on the main initiatives supported by the European Commission. Indeed we have been members of the Spinoza 2 project consortium, co-funded by the EC, where the well-known software code Optimus was developed.

But it was in 1995 that our thirst for knowledge and state-of-the-art developments culminated in the most promising initiative in Europe: the FRONTIER consortium, coordinated by British Aerospace, and targeted to develop a collaborative multi-objective design optimization environment, based on virtual prototyping technologies. The FRONTIER promise was to follow a truly native multi-objective and multi-disciplinary approach, with no shortcuts or simplifications, and treating design 'as a process', in such a way that human search could freely be interchanged with automated search. EnginSoft was committed by the FRONTIER consortium to evaluate the tool with respect both to the project targets and to the different technologies available on the market, and to present the corresponding report to the European Commission. The research turned out to an increasingly exciting journey through innovative ideas, creative solutions, and coherent IT and algorithmic choices, so that, at the end of the Journey, we decided to purchase the rights of the technology from the consortium in order to develop a comprehensive commercial product. Hence ESTECO was founded, under the vision of sharing the intellectual capital of the leading scientists of the FRONTIER consortium, and hence the software that is today known as "modeFRONTIER" came to life.



Today although EnginSoft and ESTECO are completely independent and worthy companies in their own right – we are both very proud that modeFRONTIER is a best of class product in the design process integration and multi-objective 'parametric' optimization. Indeed, some say that if you were able to unravel the 'DNA' of the software you would most likely see genes from both lineages!

Our hope is that by reading the collection of articles published here, demonstrate our passion for the technology. Furthermore, you can see how modeFRONTIER impacts the design and development process in a variety of industrial sectors; indeed you will be amazed how many products that one interacts with in their every-day lives are featured in the special edition – enjoy and become part of the growing community of business leaders that are leading in an increasingly competitive world market.

Stefano Odorizzi, EnginSoft

For more information or for support in Optimization please refer to our dedicated Competence Center:
Francesco Franchini, f.franchini@enginsoft.it
Phone: +39 0554376113

Contents

This special issue of the EnginSoft Newsletter is dedicated to ESTECO's modeFRONTIER, the integrated platform for multi-objective and multi-disciplinary design optimization. It includes a selection of new and previously published customer case studies and industrial applications that span different sectors, disciplines and technology, meant to inspire companies to take advantage of engineering simulation and optimization. These articles highlight some of the software's key capabilities and the advantages its deployment brings to organizations seeking to develop reliable products, increase product performance and reduce costs.

OUR ACKNOWLEDGEMENT AND THANKS TO ALL THE COMPANIES, UNIVERSITIES AND RESEARCH CENTRES THAT HAVE CONTRIBUTED TO THIS ISSUE OF OUR NEWSLETTER

Newsletter EnginSoft
Special Issue on modeFRONTIER - 2015

To receive a free copy of the next EnginSoft Newsletters, please contact our Marketing office at: newsletter@enginsoft.it

EnginSoft S.p.A.
24126 BERGAMO c/o Parco Scientifico Tecnologico Kilometro Rosso - Edificio A1, Via Stezzano 87
Tel. +39 035 368711 • Fax +39 0461 979215
50127 FIRENZE Via Panciatichi, 40
Tel. +39 055 4376113 • Fax +39 0461 979216
35129 PADOVA Via Giambellino, 7
Tel. +39 049 7705311 • Fax +39 0461 979217
72023 MESAGNE (BRINDISI) Via A. Murri, 2 - Z.I.
Tel. +39 0831 730194 • Fax +39 0461 979224
38123 TRENTO fraz. Mattarello - Via della Stazione, 27
Tel. +39 0461 915391 • Fax +39 0461 979201
10133 TORINO Corso Marconi, 10
Tel. +39 011 6525211 • Fax +39 0461 979218

www.enginsoft.it - www.enginsoft.com
e-mail: info@enginsoft.it

The EnginSoft Newsletter is a quarterly magazine published by EnginSoft SpA

COMPANY INTERESTS
EnginSoft GmbH - Germany
EnginSoft UK - United Kingdom
EnginSoft France - France
EnginSoft Nordic - Sweden
EnginSoft Turkey - Istanbul
www.enginsoft.com

CONSORZIO TCN www.consorziotcn.it • www.improve.it
Cascade Technologies www.cascadetechnologies.com
Reactive Search www.reactive-search.com
SimNumerica www.simnumerica.it
M3E Mathematical Methods and Models for Engineering www.m3eweb.it

ASSOCIATION INTERESTS
NAFEMS International www.nafems.it • www.nafems.org
TechNet Alliance www.technet-alliance.com

ADVERTISEMENT
For advertising opportunities, please contact our Marketing office at: newsletter@enginsoft.it

RESPONSIBLE DIRECTOR
Stefano Odorizzi - newsletter@enginsoft.it

ART DIRECTOR
Luisa Cunico - newsletter@enginsoft.it

PRINTING Grafiche Dal Piaz - Trento

Autorizzazione del Tribunale di Trento n° 1353 RS di data 2/4/2008

Carlo Poloni, President of ESTECO, takes a look back at how optimization technology has changed over the years and talks about the company's plans to expand the reach and capabilities of its technology

Looking back over the last ten-fifteen years, how has the use of optimization technology changed?

Essentially it has gone from being a specialists-only tool to becoming the norm in engineering design. Back in the 1990's, optimization tools were the purview of highly specialized designers and the tools themselves were limited in scope due mainly to the scant availability and usability of models. Because optimization was so specialized, it wasn't considered a crucial element in the design process as the problems it could be used for were limited to the area of expertise of the specialist.

The optimization process is exponentially more effective when design targets are high; if you maximize the mission of a product, the optimization becomes strategic and extremely effective. If your scope is limited to the design of a small component, it is not as strategic to the company.

In a nutshell, 15 years ago, the technology was there but it wasn't useable, or rather, it was usable only for the elite community capable of understanding its value in a small environment and in a specific application.

What's changed? How has it become the norm?

Nowadays, we have the models, the infrastructure and the decision making process, so optimization is no longer just for specialists, but for decision makers too and therefore its deployment has become strategic. We've seen this transition happen, for example in Ford, one of our major accounts. At the beginning of our collaboration, we started with the weight reduction of small components, taking a micro-approach by interacting with individual engineers. This has now evolved into a company-wide, macro-approach with different actors operating on the same level - something that has only become possible through advancements in web technology. Back in 1995, ESTECO - or rather, the founding partners, given that the company was established in 1999 - was already thinking of sharing information across companies and borders. At that time, it was technologically impossible, now it's very much a reality. It took us 10 years to transform what was an idea into something practical, useable and rock solid.

The success of ESTECO is proof of the fact that optimization has become the norm. We have seen our client base grow from a small, but prestigious, group of European customers in the automotive, manufacturing and aerospace industries – British Aerospace, Electrolux and EADS Aerospace to name a few - to today's 300-plus global clients from different industries with companies like Ford, Whirlpool, Toyota, Petrobras and Bombardier. Likewise, our company numbers have also grown: we now employ over 50 highly specialized staff and have expanded our operations to North America and India and count numerous channel partners and distributors among our ranks. On reflection, I would say that optimization isn't just the norm, it's strategic.

How has ESTECO's partnership with EnginSoft made an impact on ESTECO technology?

EnginSoft provides us with the best core competence across all engineering disciplines– from process engineering, to product and process simulation, to the use of different physics in the simulation of a component or system - a fundamental ingredient when you want to put all the aspects of product simulation together. It's with this knowledge base that we can build our vision – to use a metaphor, if ESTECO were a building, then EnginSoft is one of its pillars.

What direction do you see optimization taking in the next ten years?

The way I see it, the decision making process in optimization will become less deterministic and more social. People need to become part of the loop and have a more active role in the process.

The way things are now, customer requirements and demands are filtered through management. In the future those needs and desires will become available in the decision making process itself and open the door to interaction between who is using and who is designing the product.

The birth of the Internet showed us that sharing a process in optimization could become a reality and it took us 10 years to make it happen. Even though development times today are shorter, I expect another 5 to 10 years will pass before social tools are embedded inside the optimization framework. It hasn't been coded yet and we haven't identified how this will impact the decision making process but it is something we are working on.

Being a pioneer in the field of numerical optimization, we've come to expect innovation from ESTECO. What can we expect in the future?

Our mathematics specialists are looking at how to change objectives during the process and adapting the process to the changing environment through generative algorithms. These algorithms mimic evolution at computational speed to identify the fittest designs by creating, selecting and cycling through as many design alternatives that the algorithms automatically generate. We also have several other projects in the pipeline, so stay tuned.

ESTECO was included in the Gartner "Cool Vendors for Product Design and Lifecycle Management" Report. What does this mean for the company?

Gartner is the world's leading information technology research and advisory company and their Cool Vendor program signals small emerging innovative vendors that have unique and highly original new technology that is making a difference to the market they operate in. Essentially, it gives small companies like ESTECO a chance to shine. Obviously we are proud to be named "Cool Vendor": we have built a great company with great products and solve real customer problems and it's nice to be noticed. Given that many companies look to Cool Vendors when investigating new technologies and considering possible partnerships and collaborations, I'm sure this will raise awareness of our company and technology to companies that may not be aware of us and what our technology can do.

ESTECO is a pioneer in numerical optimization solutions, specialized in the research and development of engineering software for all stages of the simulation-driven design process. Over 250 international organizations have entrusted the modeFRONTIER multi-disciplinary and multi-objective optimization platform with accelerating product innovation across a wide spectrum of industrial sectors. ESTECO technology is distributed throughout the world by a network of qualified channel partners who provide professional local service and support. The company headquarters are located in AREA Science Park in Trieste, Italy. www.esteco.com

Gartner Disclaimer *- Gartner, Inc., Cool Vendors for Product Design and Lifecycle Management, Marc Halpern, Janet Suleski, Rick Franzosa, 08 April 2015. Gartner does not endorse any vendor, product or service depicted in its research publications, and does not advise technology users to select only those vendors with the highest ratings or other designation. Gartner research publications consist of the opinions of Gartner's research organization and should not be construed as statements of fact. Gartner disclaims all warranties, expressed or implied, with respect to this research, including any warranties of merchantability or fitness for a particular purpose.*

The top 10 benefits using modeFRONTIER
the integrated platform for multi-objective and multi-disciplinary design optimization

Advanced simulation has become a standard resource for product development in today's business world, with the continuous demand for cost savings and shorter time to market. In an ever-increasing complexity of the design process, it is now essential for engineers and R&D teams to adopt a multi-disciplinary approach, incorporating large numbers of variables, objectives, and iterations and only the most sophisticated tools grant companies to stay competitive. ESTECO has been developing and maintaining for the past 15 years cutting-edge software that allows for integration, optimization and advanced data analysis.

modeFRONTIER, the integrated platform for multi-objective and multi-disciplinary design optimization, streamlines the engineering process through innovative algorithms and integration with leading simulation software.

Business Benefit 1: modeFRONTIER promotes Automation

It is generally recognized that the direct use of the main design data model as a unifying agent in the design process forces the process to become seamless and integrated. This in turn tends to force clarification of the process itself, and a reduction in product development time. In order to carry out any significant design optimization work, an automated design evaluation capability is a prerequisite. A move towards optimization therefore reinforces this beneficial trend.

Business Benefit 2: modeFRONTIER promotes focus on Metrics

The clarification of a design's measures of success is essential to ensuring that the design team are addressing the right set of problems for the business. The use of optimization ensures that this issue is brought clearly into focus, and that the sometimes very difficult task of ensuring that sensitive areas of the problem receive their rightful attention.

Business Benefit 3: modeFRONTIER promotes closing the gaps in the Design Evaluation toolset

The use of top-down design metrics implies a completeness of capability to evaluate these metrics. Not all areas of design are currently free from difficulties in this respect.
Analysis challenges: many engineering analysis problems exist, for which only a limited solution capability exists due to their computing power resources which are not available for everyday needs.
Modelling challenges: various areas of design exist in which there are still significant challenges in developing clear agreed models of the design attributes concerned; example areas are costing and systems modelling.
Data challenges: the complete data model of a major engineering product such as an aircraft or a ship is currently much too large to be convenient for participating in 'whole design' computations.

The use of an integration & optimization tool enforces a need to provide design evaluation tools in all the areas of design which are key to the important design choices. The requirement is not to make large leaps in technology overnight, but to systematically capture the ways in which the design is evaluated in practice by the design team and formally acknowledge these.

Business Benefit 4: modeFRONTIER promotes Design for Analysis

To automate idealization, and provide closer integration between 'The Design Office' and the analysis departments (Aerodynamics, Structures, Electromagnetics, etc), the following activities have to be closely considered as part of the design process, rather than as unscheduled labour intensive and time consuming procedures:

- definition of the outside of the product
- geometry repair
- finite element model preparation
- elimination of detail

It is typical for design data to be created to a standard which is unfit for any of the above operations. Without automation of these, full use of CAD models cannot be achieved, and even the use of analysis models will be less effective. The use of modeFRONTIER will undoubtedly bring these automation issues into focus.

Business Benefit 5: modeFRONTIER promotes definition and use of operating scenarios

Top level design metrics must inevitably reflect how the product is manufactured, operated in the field, and maintained. The production and operating scenarios provide a framework that bring into focus the important cost, performance and customer satisfaction issues. The scenarios to be defined may need to encompass any or all of the following areas:

- strategic studies affecting procurement
- operational analysis of in-service use
- manufacturing cost models
- business models: (single company site; dispersed company; collaborative project)

Business Benefit 6: modeFRONTIER provides a means for rapid organizational learning

Often, an organization's know-how is what keeps it in business and ahead of its competitors. This know-how is the collective distillation of experience from having done similar jobs before and built up knowledge of the designs. Design optimization, which allows thousands of designs to be experimented with on a computer, speeds up this learning process. By trying out designs which are diverse, it promotes a broadening of knowledge of the solution possibilities and increases engineering understanding. If the results of investigating a broader design range are condensed and stored suitably, an advanced knowledge base begins to evolve for future reference.

Business Benefit 7: modeFRONTIER provides a means of outperforming the competition

For many industries, time to market is a key issue. The ability to consider and evaluate many designs in a short period of time may result in a decisive advantage over the competition. Many clients state this benefit alone provides the ROI for the software investment.

Business Benefit 8: modeFRONTIER promotes upfront optimization

By anticipating the simulation phase at the beginning of the product life cycle, modeFRONTIER optimization tool can considerably reduce design cycle and development time. This often leads to design solutions that otherwise would have been dismissed and that, often times, direct teams to surprising savings. The outcome is better coordination in product strategies and better planning which can alleviate time-to-market pressure.

Business Benefit 9: modeFRONTIER reduces simulation cost

Engineers can consistently reduce computational effort in terms of time and resources with modeFRONTIER Grid Tool and HPC exploitation resources. modeFRONTIER flexible environment allows the creation of a seamless process to exploit both local resources and remote cluster reducing dramatically the time for Decision Making.

Business Benefit 10: modeFRONTIER caters to different customers' demands

modeFRONTIER empowers the user to outline the appropriate optimization strategy, according to the design space boundaries and to the reliability and robustness sought. The algorithms families encompass both RSM-based and direct optimization, managing efficiently problem dimensions and the attainable computational resources.

Multi-Objective Optimization of Vehicle Handling & Comfort Performances

This article illustrates an application example in the field of Vehicle Dynamics. The study focuses on the simulation of the Handling and Comfort performance of the vehicle with the objective to optimize both aspects. The simulations are performed in the Multibody environment MSC.ADAMS/Car or more precisely, the customized version Fiat MB-SHARC. Automatic post-processing in MB-SHARC enables designers and engineers to monitor key parameters representing Handling and Ride-Comfort performances, taking into account both the stability as well as more subjective-related parameters to define a set of optimum solutions. The application presented here deals with the optimization of suspension mount characteristics. The process involved an initial DOE (Design of Experiments method) that allowed to select influent input variables and representative objectives and constraints. The consequent MOGA Optimization lead to a Pareto FRONTIER containing optimum solutions from various and conflicting aspects. Improvements in the overall Handling and Comfort performances, and most importantly, an understanding of the correlation between all input variables and vehicle's performances could be achieved.

FIAT CHRYSLER AUTOMOBILES

Multi-objective Optimization Handling & Comfort

The trade-off between Ride-Comfort and Handling targets represents a challenging task in a vehicle development project. Depending on brand and vehicle type (commercial-, passenger- or sports car), priorities between conflicting objectives vary, hence the weighting of single performances has to be evaluated differently for every single project.

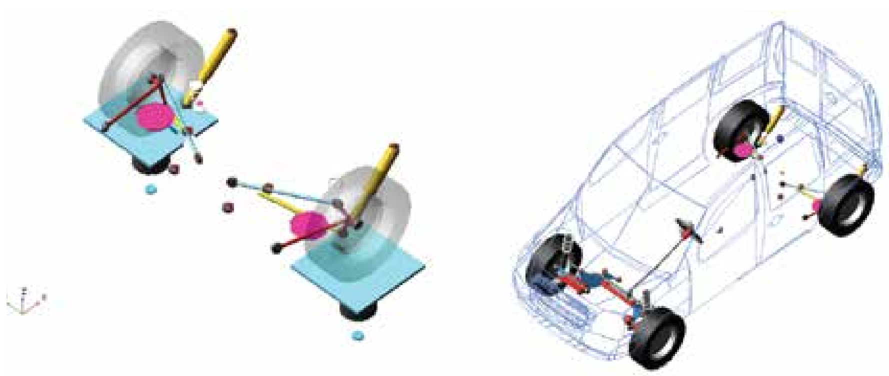


Figure 1 - Multibody Models: Rear Suspension and Full-Vehicle Handling Model - assembling Front Suspension, Steering system, Anti-roll-bar, Driveline, Engine, Rear Suspension, Body and Front & Rear Tires

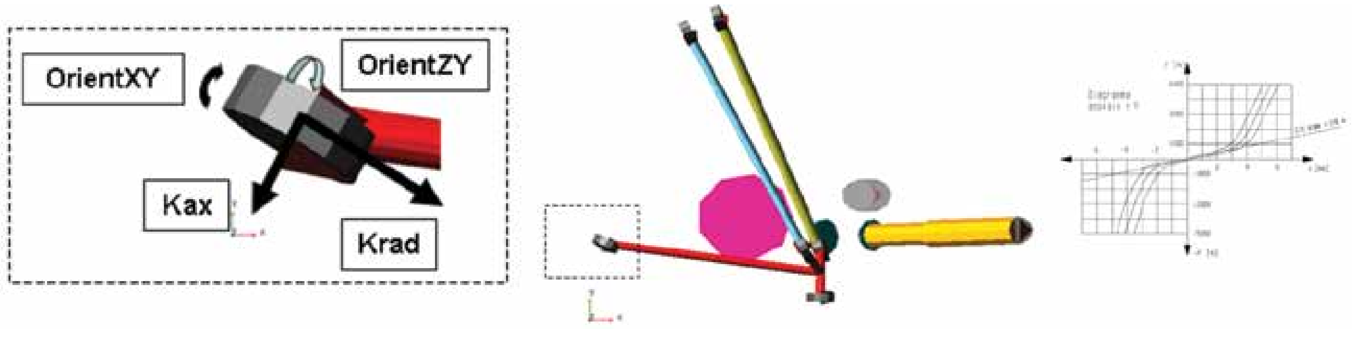


Figure 2 - Input variables: Rear suspension longitudinal arm attachment orientation and characteristics

Application

The aim of this work was to optimize conflicting aspects with regard to Ride&Comfort performances and Handling performances of a light commercial vehicle. Besides performances, the robustness of the solution was an important factor when choosing the optimized set-up.

Simulation Models and Calculation Environments

To simulate the Comfort and Handling performance, two Full-Vehicle models were used, for Comfort and Handling respectively. Prior to this and to verify constraints related to, for example vehicle height from ground, two suspension models were used – a Front and Rear Suspension model.

All models were assembled in the Multibody environment of MSC.ADAMS/Car, and the customized version Fiat MB-SHARC which enable the designer to perform special maneuvers as well as a complete post-processing and calculation of synthesis parameters of interest.

The extremely short calculation time in the Multibody environment allows to include an important number of designs covering several input variables and their full range of interest.

Input Variables, Study Constraints and Objectives

The chosen input variables must provide significant parameters for both, the Handling and Comfort performances. Typically, they can be synthesized in the front and rear suspension spring, bump stop and damper characteristics. In the application presented here though, an especially influent suspension mount was monitored.

Input variables:

- Rear suspension bushing pt1 – stiffness's and orientations

Constraints concerned mount feasible characteristics and working points during maneuvers.

The objectives included significant Comfort and Handling synthesis parameters, such as yaw velocity, sideslip angle gain, peak accelerations and time dissipation in seat rail during comfort missions.

Objectives:

- 2 Handling
- 2 Comfort

Besides these objectives, a long list of other K&C, Handling and Comfort parameters of interest was monitored.

Application Results

An initial DOE allowed to validate the important influence of each input variable and to check the significance of the constraints thus ensuring objectives are met.

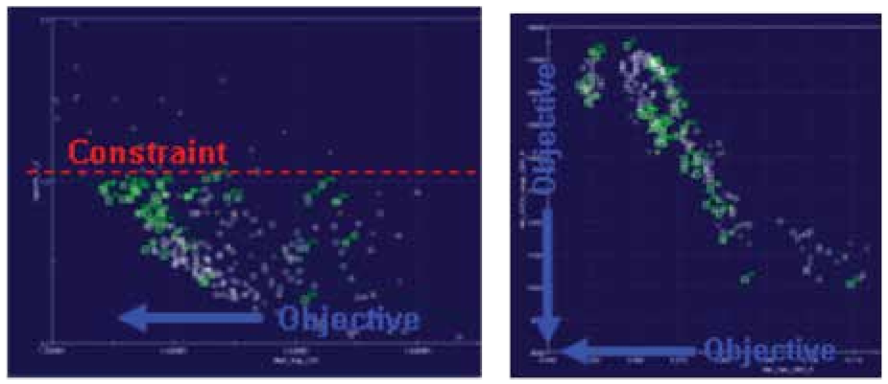


Figure 3 - Objective Scatter Charts: The left illustrates the tendency of a Handling objective modifying the ratio between the radial and axial stiffness of the bushing. On the right, an example of two conflicting objectives

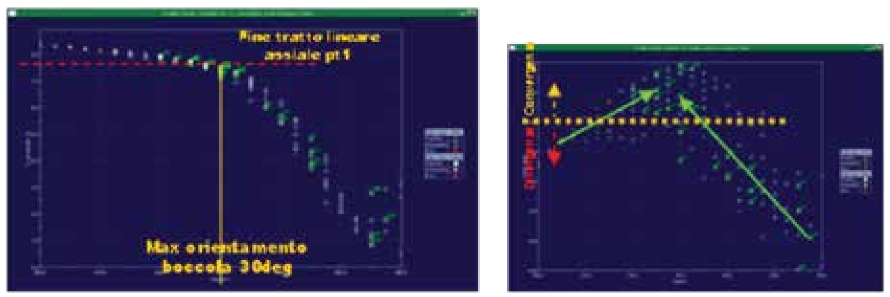


Figure 4 - Influence Scatter Charts: The left illustrates the influence of the orientation of the bushing in the X-Y plane. The right, an elasto-cinematic parameter monitored as a function of the same input variable

A Sobol DOE Study was executed and, on the basis of approximately 1000 designs, a MOGA-II optimization was performed.

Given the conflicting objectives, the optimization obviously did not lead to an optimum set-up, but to a pareto FRONTIER containing several set-ups. The reverse tendency of some parameters was confirmed. However, compared to the initial, already manually optimized set-up, some significant improvements could be achieved.

The optimization provided clear indications for the optimum values of the input variables, especially with respect to the orientation of the bushing and the ratio between its axial and radial stiffness.

After the most promising configurations were selected to weight the four objectives, and besides analyzing the synthesis parameters, the improvements were evaluated thus launching all maneuvers of interest and analyzing the time-histories and graphs of every single maneuver. Usually, this verifying stage includes more maneuvers to guarantee the solutions on a broader prospective.
The real graphs confirmed significant improvements of most of the parameters.

Robust Design Study

The study concerning the robustness of the solution was performed accordingly with the optimization. The study consisted in analyzing a set of representative pareto FRONTIER configurations to focus on the STDEV of the main parameters of interest.
Taking into consideration the production tolerances of the rear suspension, the robust design study showed that some of the optimum solutions not only improved the performance but also the robustness of the solution.
Adding the robust design of the solution to the primary objectives, allowed to choose a set-up which not only improved performances but also provided a more robust suspension set-up.

Conclusions

The activity involved 3 different models in MSC.ADAMS Car for a unique optimization.
The customized version of ADAMS Car MB-SHARC was used to obtain principal Handling and Comfort synthesis parameters.

The study allowed to gain a deep understanding of the influences from input variables and the correlation between all input data and performances. The optimization allowed to improve both aspects, Handling and Comfort, and enabled to choose a “best compromise” solution. The application presented here involved only a few input variables. However, and for a complete study, the optimization could be performed including also other parameters of interest.

The use of modeFRONTIER, a multi-objective optimization and design environment software, allowed to save time and hence to focus on and to analyze the results thus reducing the efforts spent normally on daily continuous modifications of the models and multiple analysis. The short calculation time in the Multibody environment allowed to perform the optimization in only a few days time.

The study involving the robustness of the set-up solution, enabled designers and engineers to improve the dispersion of vehicle performance in production due to production tolerances of the suspension.

The procedure created can be applied to any other vehicle, reducing vehicle testing and experimental tuning - time and costs, and will help to approach an optimum solution, already from the start.

Christina Winge - Fiat Group Automobiles, Engineering&Design, Vehicle Dynamics & Chassis, Virtual Analysis

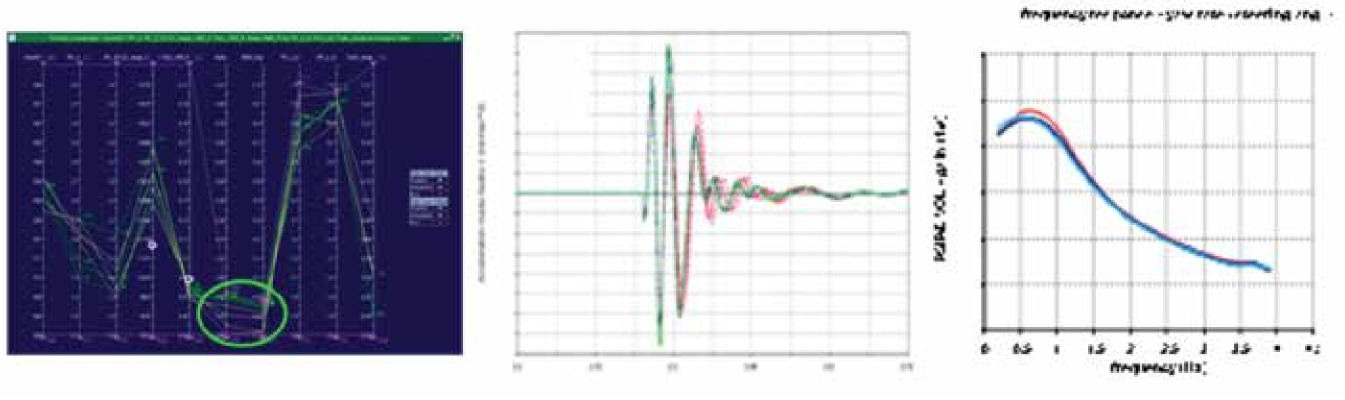


Figure 5 - Optimum set-ups: On the far left, the parallel coordinates graph illustrating some of the pareto FRONTIER solutions, in the middle and on the right, two examples of improvements obtained in a Comfort and Handling maneuver

Robust Design Optimization of a Bumper System at Volvo Cars

70% are low speed crashes

According to a recent survey by Volvo Cars Brand Experience Centre, low speed crashes represent over 70% of the crashes today. Typically crashes up to approximately 15 km/h are categorized as low speed crashes and are often caused by accidents during parking, queuing and braking situations.

VOLVO

The components of the rear part of the car are highly integrated, making repairs very expensive. Therefore, both customers and insurance companies require that the damage of a low speed crash should be limited to a few components which are easy to replace. In order to minimize the damage to the car body, the rear bumper beam must be designed to absorb all the energy from a crash. Due to the complexity and cost of repairs, the optimization of the bumper system becomes a very important and challenging topic.
Ever since its establishment, Volvo Car Corporation has put safety among its top priorities and recently a thesis work on best practices for robust design optimization of a rear bumper beam was carried out.

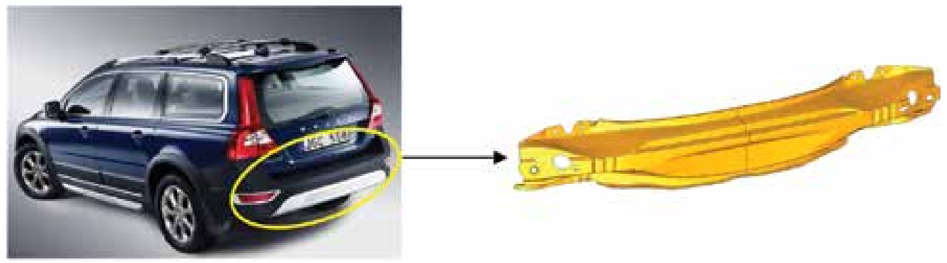


Figure 1 - Low speed crashes represent more than 70% of the crashes and combined with very high costs for repairs make robust design optimization extremely important. The study focuses on the bumper beam shown to the right

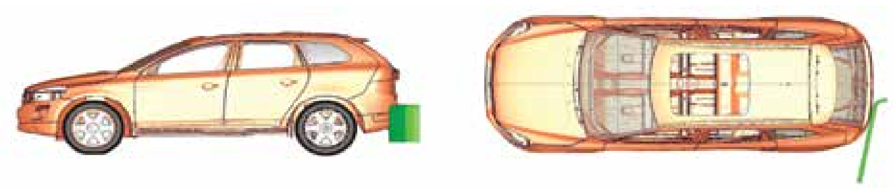


Figure 2 - Driving backwards into a fixed barrier at 15 km/h, i.e. the Allianz test, without damaging the car body is one of the toughest requirements. The figure shows the CAE model built in ANSA. This model of a full vehicle was used for verification

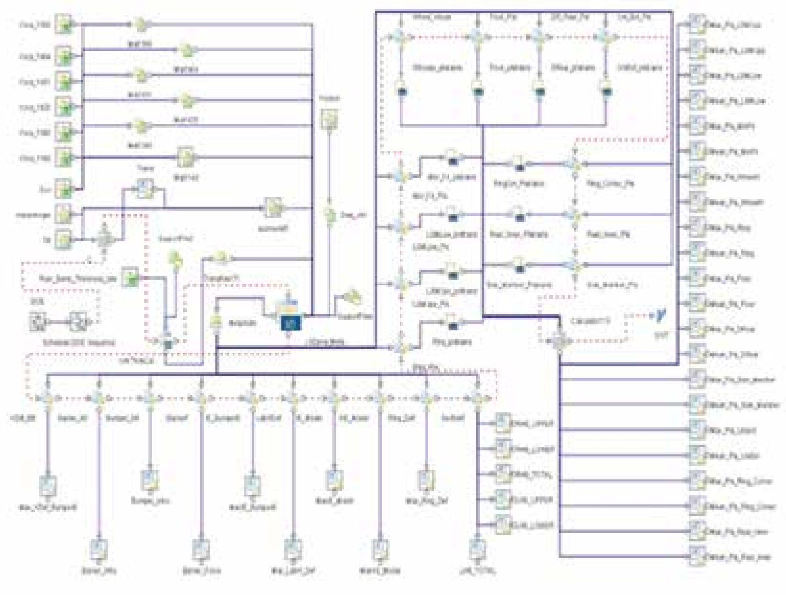


Figure 3 - modeFRONTIER was used to automate the robustness study using LS-DYNA and METApost. In order to save computational cost, a submodel instead of a full vehiclemodel was used for the robustness and metamodel evaluations

Performance varies due to tolerances in production

Using modern crash simulation software such as LS-DYNA, it is now possible to predict the behavior in a crash with good accuracy. However, everything that is manufactured has its tolerances on geometry, material properties etc which means that in practice a certain range of variation on the performance parameters always exists. Any small deviation, even a random noise, could influence the real crash, but may not be visible in the CAE analysis when nominal values are used for simulation.

A robustness study looks into groups of simulations with different combinations of input parameters, to see if they give similar responses or not. Just as with the input parameters, it is important to identify the relevant and interesting output parameters which are then traced in the robustness study. The analysis will show how the performance varies due to scatter in the input parameters.

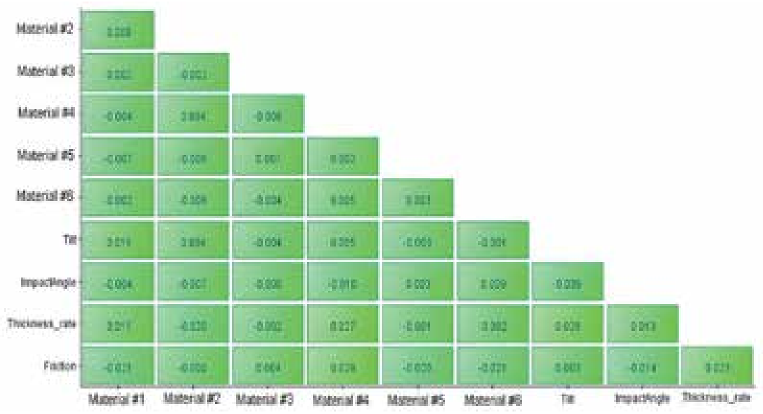
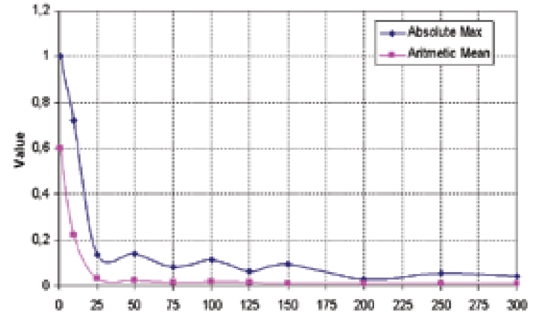


Figure 4 -Linear correlations between the 10 input variables for the Latin Hypercube sampling



# Designs	Abs Max	Arith Mean
1	1	0,6
10	0,723	0,223
25	0,134	0,033
50	0,139	0,021
75	0,081	0,015
100	0,115	0,016
125	0,062	0,012
150	0,096	0,011
200	0,029	0,009
250	0,052	0,01
300	0,042	0,008

Figure 5 - Correlation between input variables approach the ideal value of zero as the number of designs grows. A maximum correlation of 0.1 between two inputs is regarded as acceptable which corresponds to a requirement of approximately 75 to 100 samples

Evaluation of robustness

Performing a robustness study is both complex and expensive. Complex, since the crashworthiness is determined by variations in a large number of parameters, such as material properties of different parts, friction, impact angle and speed. Complexity includes both choosing the most influential parameters and implementing them for automatic evaluation. Expensive, since a single simulation takes about 2 hours using parallel execution on 24 CPUs and a robustness study may need more than 100 evaluations.

The selected input parameters in this study are:

- Material properties of the bumper beam
- Thickness of the bumper beam
- Material properties of the parts behind the bumper beam
- Barrier impact and tilt angle
- Friction

The selected output parameters are:

- Maximum plastic strain in all parts except bumper and barrier
- Mean plastic strain in all parts except bumper and barrier
- Number of high plastic strain nodes in all parts except bumper and barrier
- Maximum deformation of the bumper beam
- Kinetic and internal energy of the model
- Maximum bumper beam internal energy
- Section forces of the side member
- Latch displacements

The preferred sampling method for this type of robustness study is Latin Hypercube. A central question is how many samples are needed for the chosen 10 variables in the study. A possible answer is to study the correlations between the input variables as shown in figure 4. Figure 5 shows the absolute max and arithmetic mean of the correlation versus the number of designs. It can be seen that both values approach the ideal correlation of 0 as the number of designs grow. A correlation of 0.1 is regarded as acceptable which corresponds to about 75 to 100 samples. In the crashworthiness study, the complexity of the evaluated results as well as the number and complexity of significant interactions among the input variables may require even more samples to be evaluated in order to reach converged stochastic results.

In this study, convergence of the stochastic results of the initial sampling of 200 design points is verified by an additional 100 design points. The additional 100 designs are also generated from Latin Hypercube, but from a different random seed. This means that the additional 100 designs differ from the original 200 designs and the 300 designs as a whole still follow the Latin Hypercube space filler distribution. It is observed that there was not a big difference between the output correlations or the output distributions gained from the 200 and 300 design sets.

Results of the robustness study

One result of the robustness study is a list of the main effects for each results quantity. Figure 6 shows the effect of input parameters on the maximum internal energy of the bumper beam, ranked from most to least influential. It can be seen that the maximum internal energy of the bumper beam is critically influenced by changes to the tilt and impact angle of the barrier. In addition, an increase in the friction and a decrease in the bumper beam material strength could give higher energy absorption.

MAIN EFFECTS		INTERACTION EFFECTS	
Factors	Effect	Factors	Effect
Tilt	-1,00	Mat 5 (Side Members) * Impact Angle	0,41
Impact Angle	0,61	Tilt * BB Thickness	-0,39
Friction	0,32	Impact Angle * Friction	0,32
Mat 6 (Bumper Beam)	-0,28	Mat 4 (SM-Rear Part) * BB Thickness	0,29

Table 1 - Comparison of main and interaction effects of the inputs on maximum level of the bumper beam internal energy

Besides, the effect of each individual input parameter interactions of several inputs can be significant. As it can be seen in table 1, the combination of material properties of the rear side members and the impact angle have more effect on the results than the single factors friction or material properties of the bumper beam.

The robustness study also uncovered a set of designs giving extreme results. A separate study on these outliers revealed that they all had low values of friction. The root cause of the outliers is related to the way LS-DYNA deals with friction. As a result, 200 new FE simulations were performed with the friction fixed at the nominal value. The ranking of main and interaction effects was not affected while the output values and their distributions had to be updated. Table 2 shows how the most important stochastic data changes when friction is removed as a stochastic input variable. The table also shows that the standard deviation of the internal energy is in the order of 5-10% of the nominal value. By comparison, the number of deformed elements, i.e. elements exceeding a specified plastic strain, has a standard deviation exceeding 50% of the nominal value.

The correlation chart is a versatile tool and figure 7 shows the original 10 input variables versus 4 outputs. Marked boxes are regarded to have high values of correlation. Since the variables Tilt, Thickness, Impact Angle and Friction have many marked boxes but only one box is marked for the material properties, it is concluded that variations in material properties are of less importance than variations in the loading case.

	Bumper Beam Max IE		Number of Deformed Elements	
Nominal Value	100%		100%	
	Varied Friction	Const Friction	Varied Friction	Const Friction
Minimum	68.02%	82.21%	33.33%	62.70%
Maximum	109.59%	108.22%	557.14%	324.60%
Arithmetic Mean	96.37%	96.67%	153.17%	138.89%
Standard Deviation	7.79%	6.66%	92.86%	50.00%

Table 2 - Variation of friction has a significant effect on some of the stochastic results. It is also clear that the robustness properties can hardly be ignored when the maximum value in the study exceed the nominal value by more than 5 times

Another important result is the correlation between the outputs. Figure 8 shows that an increase in the maximum internal energy of the bumper beam leads to a decrease in the number of deformed elements on the ring frame.

The necessity of metamodels

As seen in the robustness study, the scatter of the results cannot be neglected in an optimization. Furthermore, the computational expense makes it most desirable to find a fast replacement for the FE simulation during the optimization. In modeFRONTIER there are 7 types of metamodels which aim to replace the underlying simulation model with a very fast but approximate function. The evaluation time is in the order of 0.05 seconds, making it possible to evaluate thousands of design candidates in order to solve the robust design optimization task.

The process of using metamodels is divided into 3 steps:

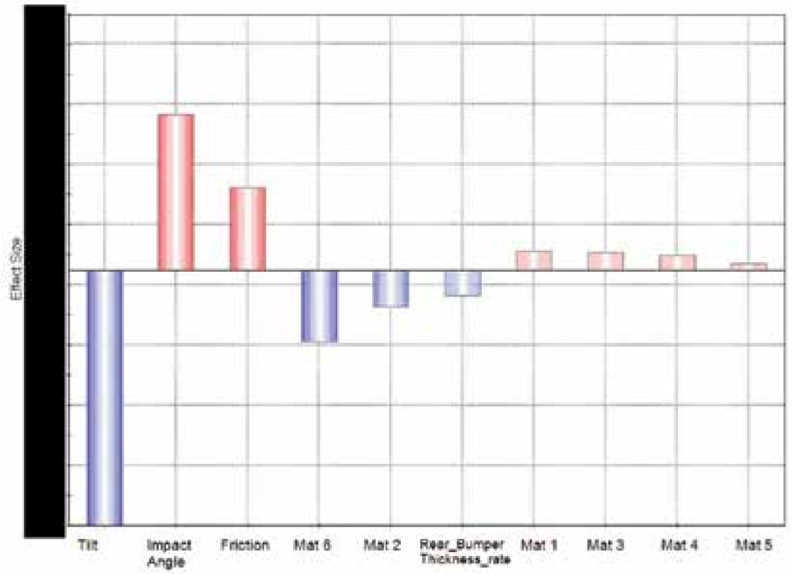


Figure 6 - The main effects plot shows that the most influential parameter on the internal energy of the bumper beam is the tilt of the barrier followed by the impact angle and friction

- Training the metamodel
- Evaluating the quality of the fit
- Using of the metamodel

It was not obvious which metamodel would deliver the best fit so Kriging, Radial Basis Function and Neural Networks were included and evaluated.

Besides the previously mentioned robustness parameters, 3 new geometry parameters, implemented through mesh morphing in ANSA, were introduced.

The training set consisted of 1000 FE simulations and another 170 FE simulations were used to check the quality of the metamodels. Figure 9 shows the difference between the Radial Basis Function and the evaluation set for one of the results. The mean residual

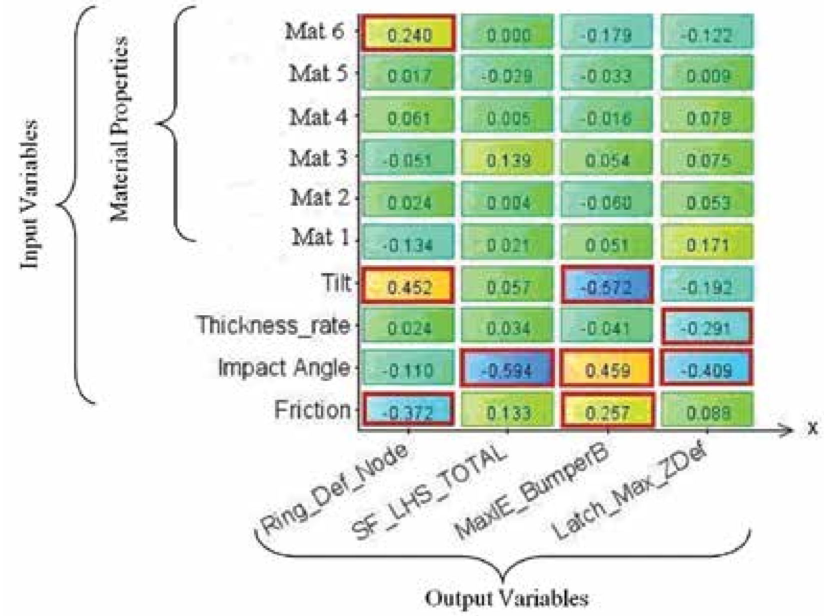


Figure 7 - Correlation between input and output variables. The variation in crashworthiness due to scatter in material properties is small if compared to the scatter in the load case variables

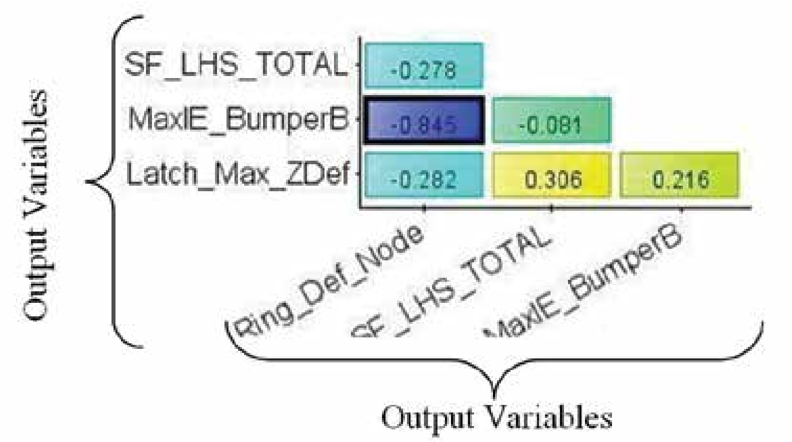


Figure 8 - Correlation between output and output variables. An increase in the internal energy is strongly correlated to fewer nodes with high strain in the ring frame

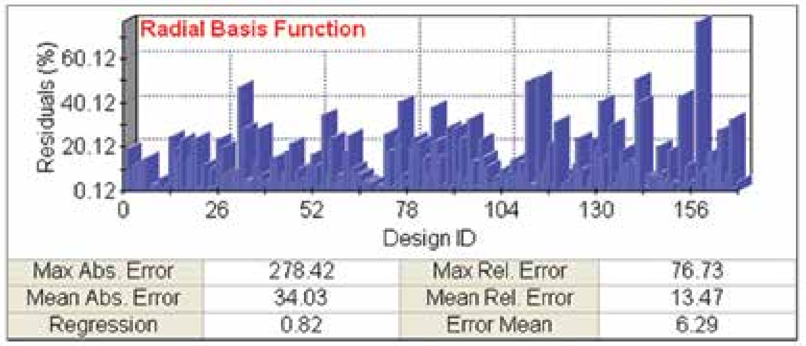


Figure 9 - The residual chart shows the difference between the forecasted value by the Radial Basis Function and the FE simulations for the evaluation set

	Number of high plastic strain elements in the ring frame	
	Original bumper beam	Optimized bumper beam
Nominal simulation	100%	71%
Minimum of stochastic simulation	63%	27%
Maximum of stochastic simulation	325%	183%
Arithmetic Mean of stochastic simulation	139%	87%
Standard Deviation of stochastic simulation	50%	32%

Table 3 - The optimized bumper has been improved in all studied outputs

values between the three methods were close and the response looked similar to the same design IDs. As such, all three methods in this study are considered to give equally good results. In the end, the parameters given by the Neural Networks were chosen for final verification.

Figure 10 - a) shows the plastic strain on the ring frame (i.e. a rear part of car body) in the submodel with original bumper beam. b) shows the plastic strain on the ring frame in the submodel with optimized bumper beam

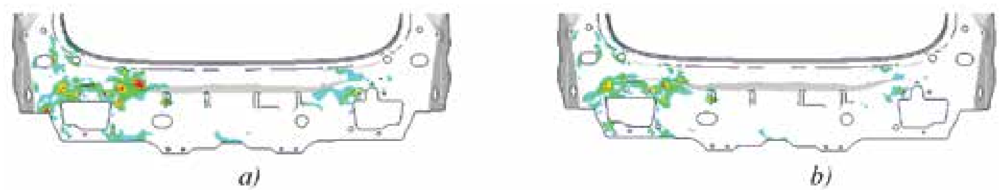


Figure 11 - a) shows the plastic strain on the ring frame in the full car model with original bumper beam. b) shows the plastic strain on the ring frame in the full car model with optimized bumper beam

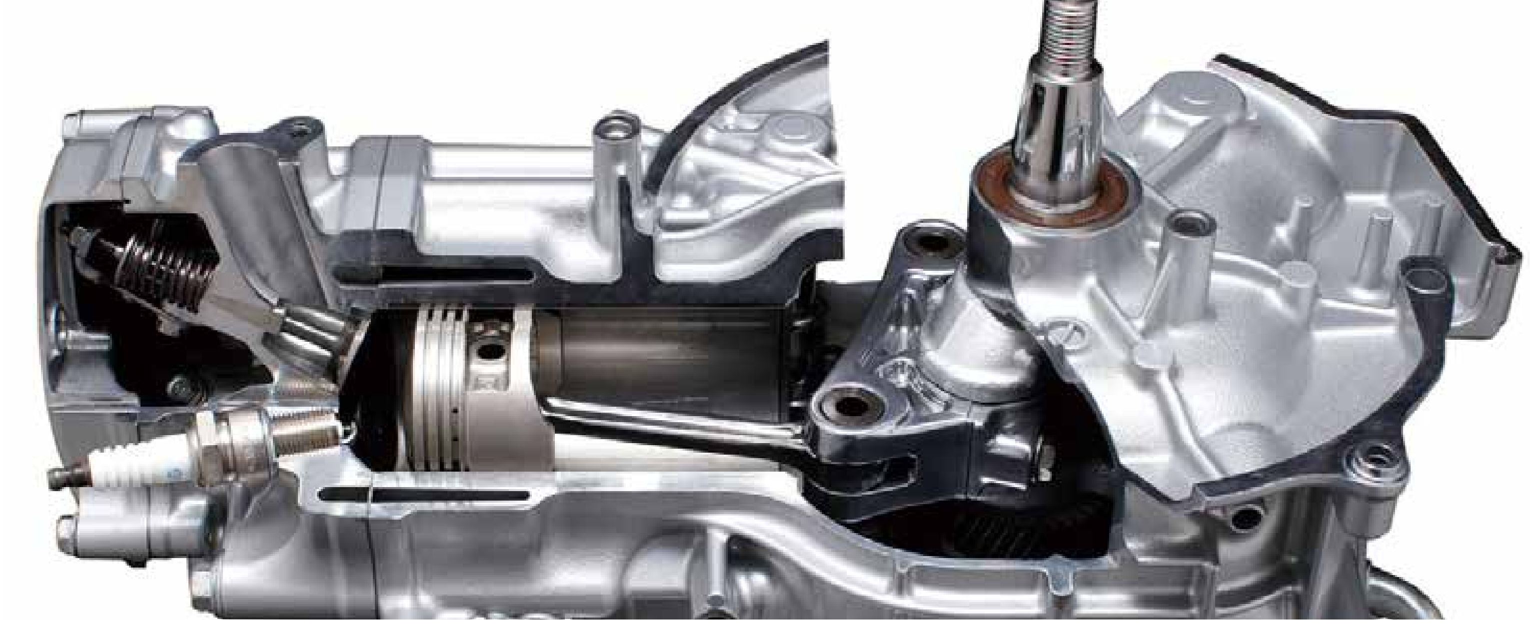
Robust Design Optimization

The metamodels were used to run a multi-objective robust design optimization. A design found through optimization on the metamodels was then selected and verified using real FE simulations. Table 3 shows results for highly strained elements and it is clear that the optimized bumper beam is a big improvement over the original. Both the mean value and standard deviation have decreased. The comparison is also done for the full car model, to confirm that results calculated from the submodel can be applied to the full car, cf. figures 10 and 11.
The bumper which was optimized according to the Allianz load case was also tested in other low and high speed crashes. The results highlighted the necessity to consider multiple load cases at the same time during the optimization.

Summary

Overall the results were very promising, proving the potential of running robust design optimization on metamodels for crash simulations. The initial robustness study also provided great value and insight into the dominant parameters and considerations regarding the FE simulations. The arithmetic mean and standard deviation for the stochastic simulations were improved for all studied outputs, e.g. for the ringframe the results were improved by about 50% and 20% respectively.

Anneli Högberg - CAE Crash Engineer, Volvo Car Corporation,
Martin Kroon - Department of Solid Mechanics, Royal Institute of Technology (KTH)
Xin Li - CAE Engineer, FS Dynamics AB
Tolga Olpak - CAE Engineer, Xdin Systems AB,
Håkan Strandberg - EnginSoft Nordic AB



Accelerating the development of general purpose engines using modeFRONTIER

Power Products R&D center, Honda R&D Co., Ltd.

Mr. Gaku Naoe, Mr. Toshiro Kiura, and Mr. Masami Okubo from the Honda R&D Company Power Products R&D Center discuss how modeFRONTIER has changed the way company approaches the product development process and shed light on how modeFRONTIER's ease-of-use and exceptional performance has made it the automotive giant's tool of choice.

Figure 1 - Mr.Okubo (left), Mr.Naoe, Mr.Kiura (right)

Honda R&D Company develops many different types of products. How do you use CAE in the R&D center to develop these products?

Mr. Kiura: Our use of CAE depends on whether it is for technical development or product development. In the first case, we use CAE for the evaluation of new technologies and to verify the possible applications. The opposite occurs in product development, where CAE is used for predicting product performance before making a prototype as it narrows down the specifications and increases the quality of test models.

Mr. Okubo: Unlike Naoe and Kimura, I work in the dedicated CAE group and support product development projects in general. I also have a role in developing simulation technologies.

One of thing we always ask our users is whether they have been successful in reducing time of development projects. Have you been able to shorten project times? How do you proceed with your projects?

Mr. Naoe: Our development times are definitely shorter than they once were. As a result, we've had to improve the accuracy of performance prediction before making prototypes. Therefore, the CAE process during the design stage is more and more important to achieving this goal.

Mr. Kiura: Project members are assigned to each technology development and product development respectively. CAE is just one of the steps during the design and testing process. In this way, by using CAE in the actual projects, we have been able to accumulate practical analysis technologies. We think this approach is more suitable for the power product business in which the products are varied and the analysis range is wider than the approach with which professional analysts use CAE. In the CAE dedicated group which Okubo belongs to, on the other hand, they deal with analysis which requires professional and advanced knowledge and developing new analysis technology for further improvement of the efficiency. Here, engineers get the opportunity to show their uniqueness and originality in

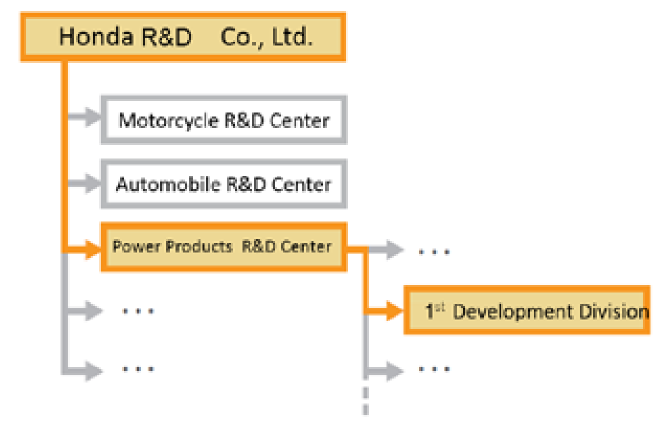


Figure 2 - Company organization chart

terms of analysis methods. However, the technologies tend to be reflect personal skills and experiences and this a problem in terms of how to manage that.

Mr. Okubo: In this context, each engineer needs to work on technology improvement for both the simulation and CAE group itself.

CAE is now an integral part of project design at Honda. When and why did you start thinking about using CAE?

Mr. Naoe: I'm in charge of sound, vibration and strength testing of general purpose engines. At university I gained experience in structural analysis and started using CAE for checking the correlation between test results and simple CAE results.

Mr. Kiura: I joined the company with the aim of working in CFD simulation. Because fluid dynamics phenomena are difficult to see, CAE plays a very important part in the understanding and clarification of that phenomena. These days, we use CAE in the development of low-emission engines, improving overall engine technology and in research towards future projects.

Back in 2007 you started using modeFRONTIER. Can you tell us the motivation behind your decision?

Mr. Naoe: We were having problems with sound and vibration on the link design of "EXlink", the extended expansion linkage engine. At the same time, my colleagues were having problems with balance cooling performance and noise in the centrifugal fan. Together, we decided to give "optimization" a try. Our experience showed us that multi-objective optimization was fundamental in solving the problems and that's when we came across modeFRONTIER.

What was your first impression of modeFRONTIER?

Mr. Naoe: The first time I used it I thought it was a nice software tool. It was surprising because it was very easy to use - I was able to use it after only half a day's training. My main task is testing and I often step away from simulation but even in those situations, I can operate intuitively and analyze problems quickly without having to resort to the manual.

What was it like before the introduction of automated optimization and simulation software?

Mr. Naoe: In the beginning, "Optimization" was often misunderstood. Everyone thought they would get an answer simply by entering some numbers. So it took some time to for our engineers to accept this new technology. As I already mentioned, we proceed with developments on a project basis. Over the years, personal responsibilities and workloads have become heavier meaning that engineers are required to develop their skills constantly. In order to let engineers know the meaning and necessity of multi-objective optimization, we carried out an educational campaign to spread this technology by showing actual case studies in our company. In the campaign, we insisted that the person in charge had the final decision and that it is important that he/she evaluate the physical phenomenon from various angles, by showing multi-dimensional analysis charts, bubble charts, and correlation charts prepared in modeFRONTIER post-processing. After that, because we had achieved results by formulating models and using post-processing capabilities, the number of users increased – modeFRONTIER's easy to use environment also played a key role in engineers adopting it as their tool of choice. In my case, being in charge of testing, it's very effective for data mining and targeting test results and not just for its integration with other CAE software. Recently we have been using its clustering capabilities.

Have you ever used modeFRONTIER for purposes other than those you've already spoken about?

Mr. Kiura: While we had tried numerical simulation in the CAE group, we had also considered applying optimization to measurement and control. As we need to collect a large amount of data for many purposes in engine measurement, model-based measurement together with multi-objective optimization is very efficient. Especially in the case when there are many control factors, choosing principle parameters and understanding the phenomenon equally as important.

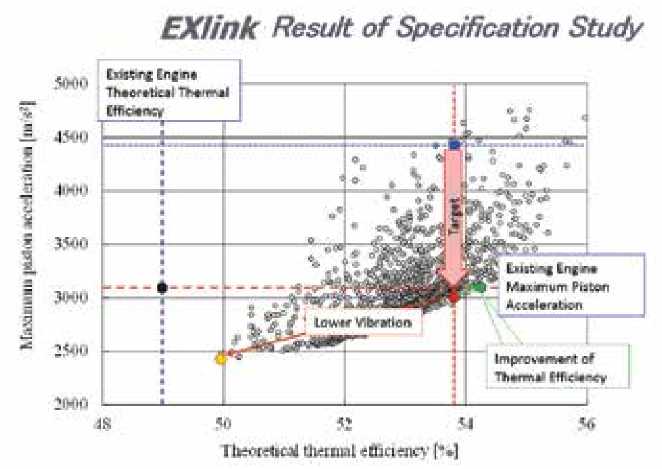


Figure 3 - Case study 1

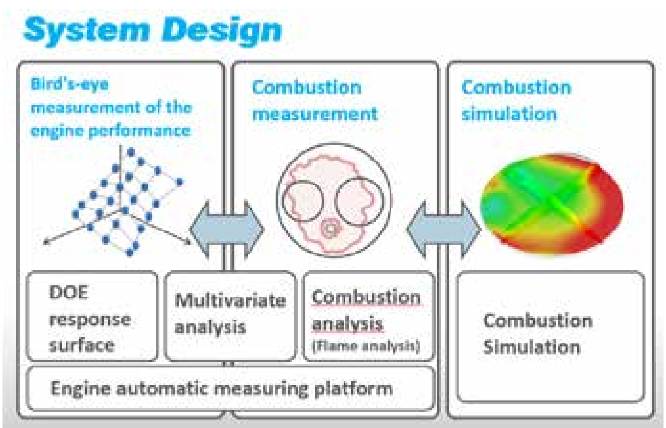


Figure 4 - Case study2

Please tell us why you use modeFRONTIER in combination with systems for engine measurement and applied fields.

Mr. Kiura: The dedicated auto driving system integrated with dynamometer makes advanced measurement possible. However the DOE, optimization algorithm and result analysis capabilities in such systems is limited. Therefore, to enhance the degree of freedom and expandability of the measurement and multi-objective optimization capability, we combined the multi-objective optimization of modeFRONTIER and the auto measurement of LabVIEW. Moreover, there were other purposes for visualizing measurement results for different parameters from various perspectives by using response surfaces and correlation charts, examining the results that designers usually trade off, and establishing the know-how for targeted designs. Not only that, in more general cases, we use modeFRONTIER to evaluate our own assumptions for the phenomena in which principle factors are not specialized for multi-objective optimization and formulation is not easy. This means that, using modeFRONTIER, we analyze from various approaches and consider the results. modeFRONTIER is our partner who helps us resolve the problem.

From your comment, I understand that you use modeFRONTIER for each step of model formulation, parameter DOE decision, auto execution, and post-processing. What is the outcome when using modeFRONTIER?

Mr. Naoe: The tests and CAE results that we've obtained so far have given us design space information and we used that data to change some conditions. Now, by using multi-objective optimization, we can predict to some extent the underlying phenomena and establish an appropriate strategy. modeFRONTIER gives us a large amount of data and we continue our studies based on that data. For example, the number of principal design parameters was traditionally about 4 for the engine mechanism. In contrast, the number of principal design parameters for EXlink increased to 11 and we were at a loss to know that the parameter studies would be around 400 million designs. We ran about 1,000 to 2,000 calculations with a modeFRONTIER genetic algorithm and found the way to maximize performance. modeFRONTIER enabled us to run the optimization 24/7 enabling us to make every minute count.

Mr. Kiura: Now we are able to explore results in areas we couldn't search before and find the design closes to the optimized result.

Could you provide some real case studies that show your use of modeFRONTIER?

Mr. Naoe: I have been involved in the research of "EXlink", the extended expansion linkage engine, as a mechanism for an extended expansion thermal cycle which makes the expansion ratio higher than the compression ratio. This mechanism offers a substantially higher thermal efficiency of the internal combustion engine. This issue considers inertia excitation force property and its reduction for the EXlink engine. As a result of the simulation, the maximum excitation from the early stage prototype multiple linkage system increased from the conventional system.

The reason is that the maximum piston acceleration during the expansion stroke in the multiple linkage system increases as compare to that of the conventional system. We performed the optimization calculation for the multiple linkage system, aiming to reduce the maximum piston acceleration, and studied the new low vibration linkage. New linkage improved the theoretical thermal efficiency by 10 % as compared to conventional system, and its the maximum piston acceleration was able to be lower than that of the conventional system.(Fig.3)

Mr. Kiura: We have been working on research and development toward further improvement of thermal efficiency and reduction of emissions, noise, and vibration, of general purpose engines. We have established an engine performance diagnosis system by combining the optimization technology and response surface methods, engine combustion diagnosis technology, and numerical computation technology. This system offers an overview measurement of the engine performance by using the response surface method, identification of the control factors using optimization technology, measurement of flame, and clarification of the combustion mechanism by numerical computation.

What are your plans for using modeFRONTIER in the future?

Mr. Okubo: The problem that we have is increasing resistance and reducing the weight of engine components. Our intention is to achieve this through optimization. As there are more opportunities to use simulation technology, I would like to extend it to more users in our company.

IDAJ Co., LTD. is one of the most successful CAE companies in Japan with its high skilled engineering expertise and broad range of services. As the integrated CAE solution provider, IDAJ is distributing more than 20 different CAE software. Its highly reputed diverse offering has been underlined by numerous success stories and testimonials from many satisfied customers and software venders in the automotive, precision, energy, heavy industry and home appliances industries. IDAJ aims to provide the best solution to its customers, by offering comprehensive integrated solution technologies with multiple discipline CAE approach as the core competence. The company headquarter is located in Yokohama, Japan with several subsidiaries in China, Korea, UK and North America.

Figure 5 - Salad CG FFV300 – The second version of gas canister tillers. It's large in tillage width and can be used for both amateur gardeners and professional farmers

Figure 6 - The home-use gas engine cogeneration unit - Self-sustained operation is available in case of a power outage. The EXlink's high expansion stroke engine realized substantially higher thermal efficiency than a conventional engine

Tyre set-up for commercial vehicle
multi-body model: modeFRONTIER as a calibration tool

Iveco is an international leader in the development, manufacture, marketing and servicing of a vast range of light, medium and heavy commercial vehicles. It is endowed with a worldwide commercial network of sale outlets and service points, and strives to provide its customers with class-leading performances. Iveco currently employs over 25000 people all over the world and is present in all five continents. Its products have been renowned for many years as a valuable work tool for the most diverse applications.

Introduction
Reliability is perhaps the most important feature required from a commercial vehicle, and it must be guaranteed even on the most challenging missions without sacrificing ride comfort. To address these issues, in the Virtual Analysis Department of Iveco we developed multi-body models in order to predict vehicle robustness and comfort since the earliest product development stages. In such models, tyres are one of the most critical components to set up, since their effect on the global vehicle behaviour is remarkable and their modelling very complex.

There is currently a great variety of tyre models available to simulate tyre behaviour in multi-body simulations: the one used for this study is Ftire. Ftire is a physical model which describes the most important tyre phenomena, encompassing stiffness nonlinearities, ring flexibility, internal damping, friction, and so on. A very useful feature of Ftire, which makes its use intuitive, is that its input parameters are physical quantities and not just numerical coefficients. These parameters, however, are not fed directly into the tyre model, but are pre-processed to build a mechanical system whose behaviour reflects the original input characteristics. This aspect constitutes a complication in the model set-up, since the passage from input parameters to model is not immediate, with possibly significant interactions among parameters. To fully exploit Ftire potentialities, it is necessary therefore to make use of a tool which allows managing correctly such a complex model. In this article, we describe our experience in using modeFRONTIER as a tool for calibrating Ftire models. The ultimate goal was to achieve a good numerical-experimental correlation in order to make significant reliability and comfort predictions by means of multi-body models. The vehicle used throughout the analysis is an Iveco Daily Van.

Input data
As a starting point, we used an Ftire model developed by a tyre manufacturer, which reproduces experimental data obtained from tyre test rig. Though originating from an experimental campaign,

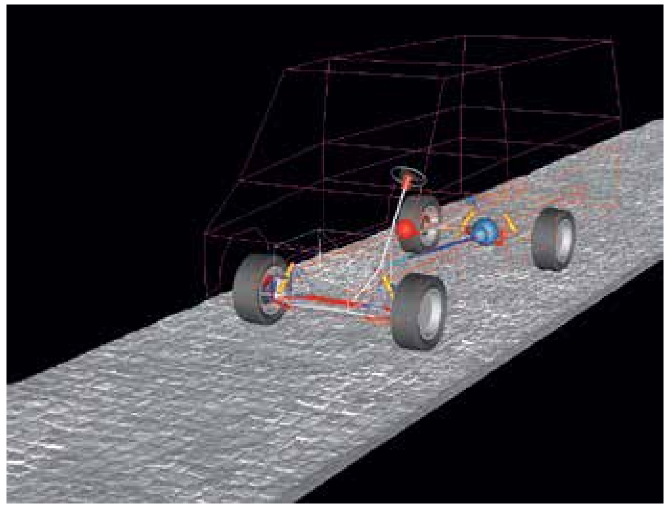


Figure 1 - Multi-body model of Iveco Daily driving on Belgian blocks test track

this model needs further calibrating because of several reasons. Firstly, the calibration must be focused on a specific application, since different tasks involve different phenomena. For comfort and reliability tests as in our case, the model should correctly reproduce processes occurring at frequencies up to about 35 Hz, while for other applications, such as vibrations, higher frequencies are usually of interest. Limiting the range of phenomena permits to tailor the model for a specific task, simplifying the procedure and allowing to achieve better results than it would be possible to obtain

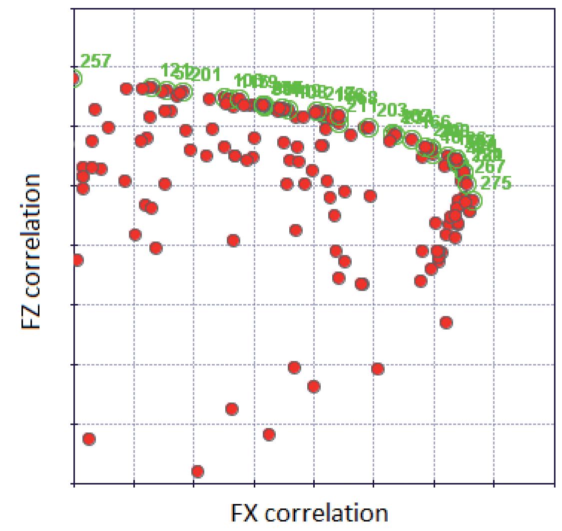


Figure 2 - Pareto frontier of numerical-experimental correlation of forces acting along X and Z directions

with a general calibration. Besides, test rig data are not complete, since in real usage tyres interact with vehicle suspensions, which of course are not present in tyre test rig.

The experimental basis for the analysis was created through an extensive measurement campaign on an instrumented vehicle. The vehicle was driven on several different tracks with a contemporary acquisition of tyre forces by means of Wheel Force Transducers (WFTs). Moreover, accelerations and suspension strokes were measured. These signals are used as reference time histories in the model set-up. Finally, all test tracks were laser scanned in order to have a faithful 3D representation of the roads. The numerical data were processed in order to provide a digital depiction of the track in the multi-body simulation environment.

Procedure
The rationale behind the calibration process is to test the tyre behaviour on tracks of different complexity in order to assess both the tyre behaviour and its interaction with the suspensions. The reference tracks used in the analysis are

- cleat
- pothole
- Belgian blocks

The cleat and pothole provide as result force and acceleration time histories which can be compared directly between the experimental data and the numerical simulations. The cleat, in particular, includes mainly the tyre enveloping capability, while in the pothole interactions with vehicle suspensions start to have a larger role. Once calibrated the model on these two tracks, the Belgian block track is used to give a final confirmation of the results, as well as to infer about the model predictivity on a real track which is typically used for fatigue and comfort analyses (Fig. 1). The results obtained from the Belgian block track are processed with statistical procedures.

The tyre model calibration was considered as a particular case of optimization, in which for each design the input parameters are the tyre properties, and the outputs are the correlations between the experimental and numerical signals. The objective is to maximize such correlations. The time histories were compared both in time and frequency domain, in order to make sure that the similarity between experimental and numerical data is not only a numerical effect, but it is a token that the occurring phenomena are actually represented in a correct way in the model. All the procedures described hereafter were applied both on front and rear tyre data.

Due to the high number of parameters in the model, the first step we took was to perform a general optimization with the only scope to understand which parameters are influent and which can be discarded as less important. Starting with 20 initial parameters varying within a broad range, it was eventually shown that only 7

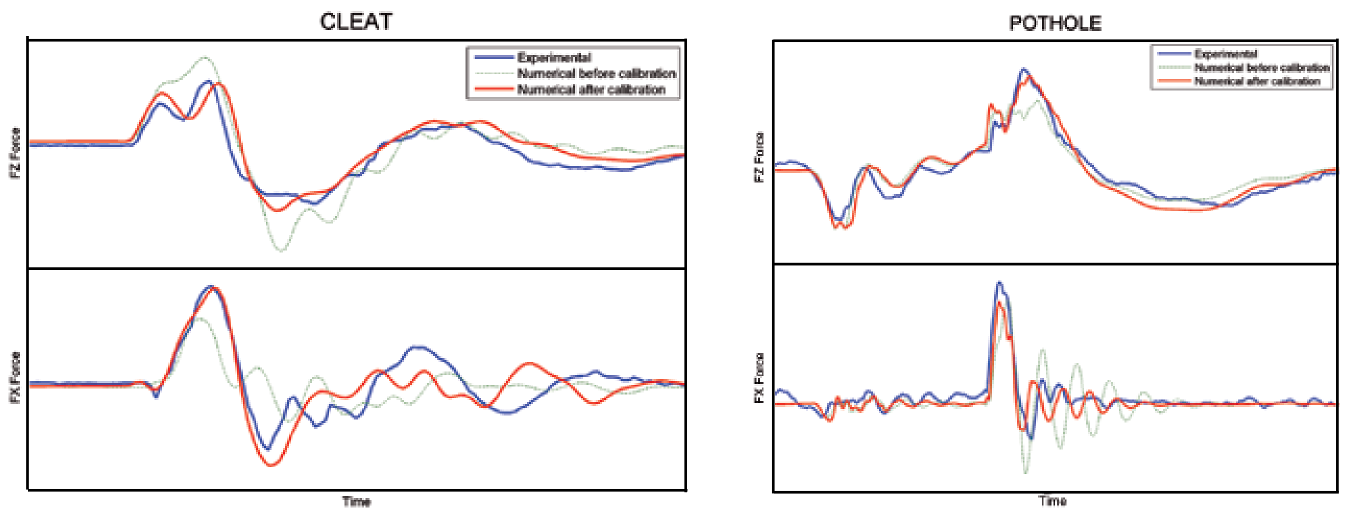


Figure 3 - Comparisons of experimental and numerical wheel forces on cleat and pothole

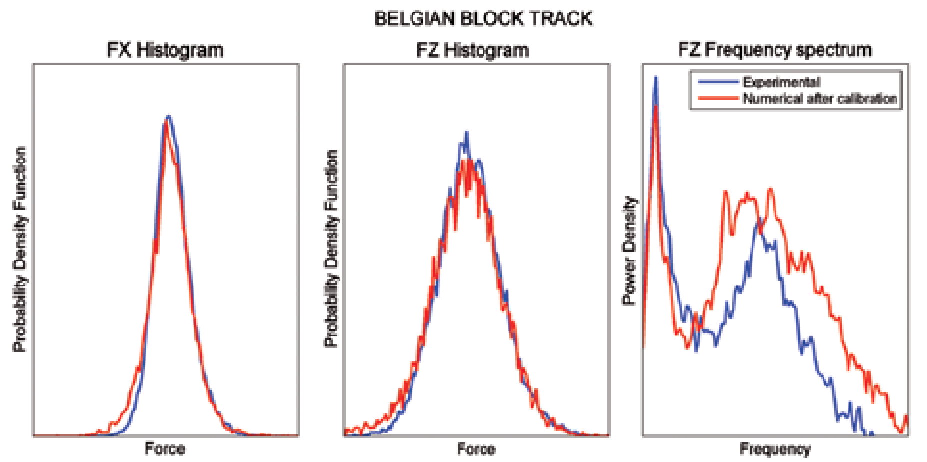


Figure 4 - Comparison between numerical and experimental histograms and spectra of the wheel forces measured on the Belgian block track

of them were truly important. The other parameters had a small influence on the final outcome, so that the further steps could be simplified by neglecting them.
After identifying the main inputs, a proper calibration was carried out. In general, the challenging task was to design a unique tyre which provides high numerical-experimental correlation on wheel forces acting both in X and Z directions. The algorithm chosen was a MOGA-II. After about 500 designs it was possible to define a neat Pareto frontier (Fig. 2).
Seeing these encouraging results, the vehicle model was revised by modifying some stiffness and damping parameters of the suspensions. After that, a finer optimization was performed with parameters varying in a small range with a reduced step. This new analysis led eventually to the definition of an even more accurate tyre. Fig. 3 compares the experimental signals with those produced by the tyre model before and after the calibration when the vehicle drives on cleat and pothole.
The final test was to compare the results obtained on Belgian block track. Fig. 4 shows the results. By comparing histograms and spectra, it can be stated that the tyre model reproduces all the phenomena occurring in the frequency range of interest, with a magnitude equivalent to that measured on tracks. This allows to infer that the results supplied by these numerical simulations are correct to estimate load ranges and fatigue life of vehicle components.

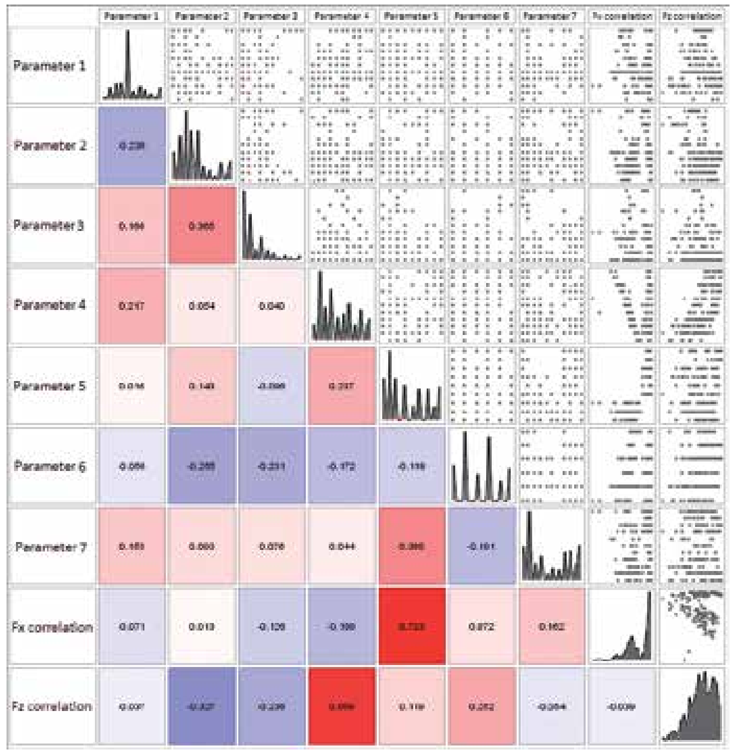


Figure 5 - Cross-correlation among input parameters and output variables (force correlations)

Discussion and conclusions

The model set-up greatly benefited from splitting the analysis into a series of different optimizations each with a different goal. In particular, the first was meant to define the range of parameters which were truly significant for the task, while the successive ones represent the real model calibration, the last one resulting as a final refinement. This multi-step approach allowed reducing the complexity of the model as much as possible while preserving its capability to achieve good experimental-numerical correlation.
Another important aspect of this result is that it enabled a simple understanding of the influence of the various parameters on the different signals. It was found, indeed, that the ability to catch the longitudinal phenomena was to some extent in competition with the possibility to correctly represent the events occurring in vertical direction. A statistical analysis performed in modeFRONTIER allowed to sort all parameters according to their relevance for longitudinal and vertical phenomena, evidencing conflicts and indicating what trade-offs had to be made (Fig. 5). It is worth remarking that the ability to manipulate with insight an Ftire model should be considered as an important result as the new models obtained.

In conclusion, it was possible to create tyre models with an excellent numerical-experimental correlation and to gain understanding of such models. For the future, this will allow to increase customer satisfaction with no cost increase and permit the engineering department to have at its disposal both a tool and a methodology to tackle reliability and comfort issues.

Acknowledgements
I would like to thank my colleagues ing. F. Ragusa and ing. F. Cristiano for the help and support provided throughout the work, as well as for the useful and insightful discussions.

Roberto Bianco - Iveco

Multi-objective optimization on the timing system of a small 2-wheeler engine (SOHC): methodology and case study

In recent years 2-wheeler engine companies have been focused on increasing overall engine efficiency, which can be achieved by resolving factors such as, engine down-speeding, engine down-sizing and by reducing the frictions. However, to maintain or improve vehicle performance, it is necessary to provide a corresponding increase in specific power. In accordance with these trends, the studied approaches and methodologies have been exploited, during the development of the new Piaggio small scooter engine.
In this project, a multi-objective analysis was applied to the valve train system design, in order to optimize the engine performance in terms of friction reduction, power curve and timing system response. These calculation methodologies have been followed using the modeFRONTIER platform for the multi-objective optimization analysis and the commercial simulation software GT–SUITE.
The several configurations investigated obtained the desired trade-off between the appropriate and efficient valve train behavior and the engine performance. The global engine friction reduction was therefore obtained thanks to low resisting cam torque profiles and a specific valve springs set up.

Introduction

The growing demands for fuel economy in recent years calls for development and application of new efficient technologies, resulting in resolving rising fuel prices, adhering to the more stringent government fuel economy standards and awareness of increasing environmental impact. In view of this scenario, the control of engine frictions (in other terms fuel efficiency) and performance in internal combustion engines becomes decisive to provide a competitive vehicle for 2-wheels mobility and the use of numerical models and calculation methodologies provide an important support in pursuing these goals.

PIAGGIO &C.s.p.a.

The methodology followed is based on the development of an optimization model. It investigates and finds out the appropriate valve lift event shape, with the objective of maintaining or increasing engine performance and also fulfilling the objective to minimize the resisting cam torque in conjunction with design constraints satisfaction.
The cam design started from a multi-polynomial valve lift curve and is fundamental in designing the timing system to take into account valve train stability, durability and noise, as well as engine breathing.
The valve train system is one of the major parts of internal combustion engine: the valves draw the air and fuel into the cylinders and allow the exhaust gas out. Therefore the method to design valve lift profiles and the valve train components are essential in defining the engine performance, valve train durability and NVH. The valve train system should be optimized to avoid abnormal valve movement (jump or bounce phenomena) throughout the engine's speed range.
Another advantage of in optimizing valve events is that, cam follower separation speed is increased, valve spring margin is improved and cam torque resistance is reduced. This allows the design of a new valve spring setup, with lower loads and mass, in order to reduce frictions.
This work aims to demonstrate the effectiveness of the optimization methodology and its robust practical application to the scooter's engine valve timing: the described approaches have been exploited for the development of the new Piaggio scooter engine (125cc, 4-stroke,

1-cylinder, 4-valves), whose valve train arrangement includes a SOHC (Single OverHead Camshaft) with a roller follower.
The project start with existing valve lift profiles (intake and exhaust), referring to the 125cc 3-valves engine. These profiles have been adopted initially for 4-valves new engine. The exploitation of the methodology described provided a new optimized valve lift event configuration.

Valve lift profile design optimization

The valve lift event is one of the most important factors when improving an engine's performance by maximizing the area under the valve lift curve. But it is also true that each engine working condition needs a certain amount of charge to be trapped into the cylinder, depending on engine speed is required to optimize.
It would be desirable if the valves were opened and closed as quickly as possible, however the lift area integral is limited by certain kinematic constraints. Therefore when a new valve lift profile is conceived the designer needs to evaluate whether the guidelines are satisfied or not, such as maximum positive and minimum negative acceleration, valve-piston distance, Hertzian stress at the cam lobes-roller interface, minimum cam radius of curvature, spring margin to avoid cam-follower separation, etc.
Manually modifying the lift event can be time consuming when trying to satisfy the valve train recommendations and have a direct feedback of the engine response across the operating speed range. It is therefore becomes important to automate the process of controlling the engine and valve train system behavior.

The automated process has been created within modeFRONTIER to perform a multi-objective optimization of the calculation software (GT-SUITE), used to evaluate engine performance and valve train system behaviour.
In Figure 1 a snapshot of the workflow of the entire optimization model is shown (to improve the readability, the data workflow is represented by subsystems).

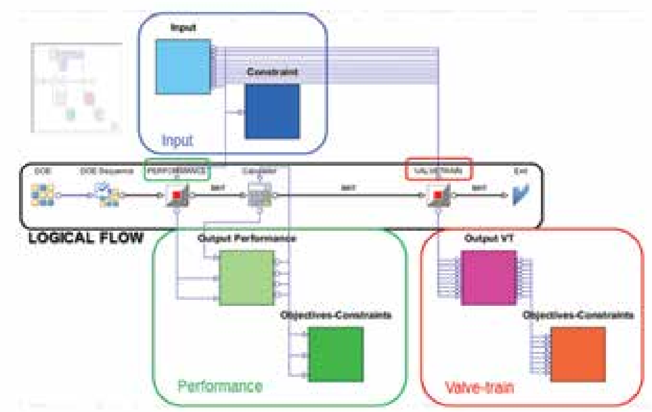


Figure 1 - Snapshot of the workflow of the entire optimization process

The model workflow in Figure 1 shows two data flows: logical and data flow. The first is the sequence of operations performed automatically by modeFRONTIER during the optimization. This logical flow consists of initial DOE and Scheduler "node". These are the twin "node" that drives the whole optimization process. In particular the scheduler is the "engine" that learns from results of each simulation and plans the next step to improve the input variables and fulfill the objectives. Central to this process are two nodes built using GT-SUITE to perform the operations to reach the goal.
The data flow begins from the input variables and ends with the output variables, which can become objectives or design constraints (the details of this phase will be described hereafter).

Input parameters for the multi-polynomial design approach

The optimization model starts with the definition of a certain valve lift event. A valve profile design process generally begins with defining the shape of the valve acceleration curve. In this work a representation with a multi-polynomial approach is described and applied to the valve acceleration and consequently to the valve lift definition.
The design technique to identify the valve acceleration is based on a multiple-polynomial scheme. The profile is divided into a total of 14 zones and the shape of the profile in each zone is modeled with a 5th order polynomial. In this process of lift curve synthesis the constraints on derivatives of lift are expressed in terms of non-dimensional design parameters.
The half-cam profile acceleration curve schematic (excluding ramps) and zone lengths and non-dimensional design parameters are shown in Figure 2 (in the model described a symmetrical type of the lift profile has been defined).

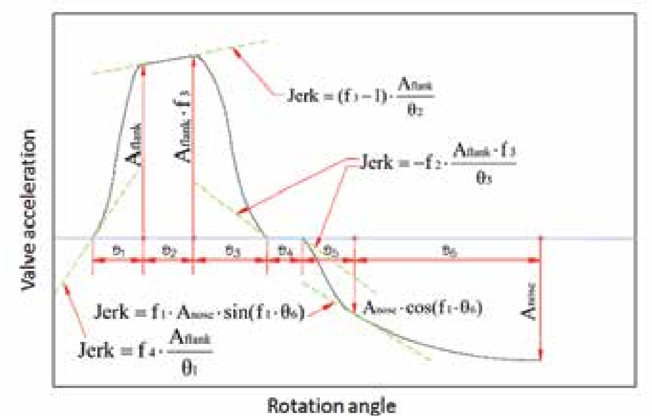


Figure 2 - Half-cam profile acceleration curve

Therefore 10 design parameters have been selected in the optimization analysis to modify the shape of the acceleration curve and they have been constrained in modeFRONTIER to vary in a certain range conveniently defined. They are shown in Table 1. The total lift event duration, computed indirectly using lengths of zones 1-6, has been constrained to maintain an appropriate value. The duration of the cam ramp is calculated by the solver based on the input for ramp type, ramp height and ramp velocity. Afterwards, specifying the maximum lift, the solver is able to find a solution for flank and nose acceleration (Figure 2). The valve timing anchor has been maintained constant.

Input variable	Description
θ1	Angular durations for each zone of half-cam profile acceleration
θ2	
θ3	
θ5	
θ6	
f1	Non-dimensional parameters to define jerk in each junction point
f2	
f3	
f4	
H_max	Maximum valve lift event

Table 1 - Design parameters defined in the model

The choice adopted during this application with regard to the input variables definition until now described, as well as the output variables, in particular objectives and constraints settled for the optimization process, is meant to represent one of the potential applications in relation to using this methodology. Any other considered problem configuration could be applied and evaluated, in order to satisfy any other design constraint and fulfill whichever objective based on user needs and targets. The model build-up in modeFRONTIER follows a modular approach to the problem.

Engine CFD and valve train model node description

During the optimization loop the first step has consisted in having the solver node run the engine simulation. The commercial code used to build the numerical model has been GT-POWER (the blocks diagram of engine model is shown in Figure 3). The above mentioned 125cc displacement, 4-stroke engine has been modeled (1D simulation).
The good predictivity of the model about the behavior of the engine related phenomena, can be seen in Figure 4.

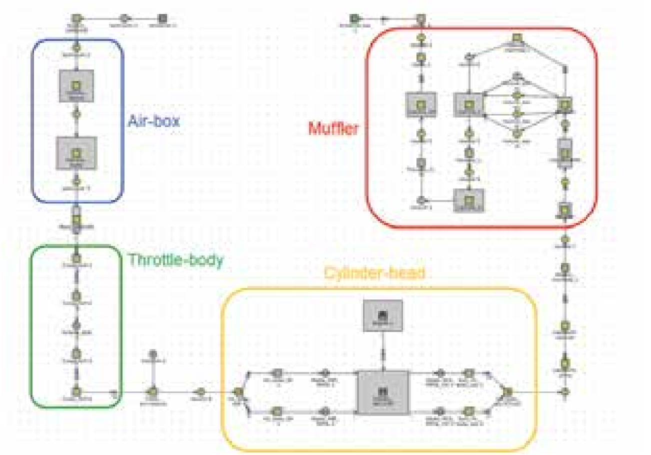


Figure 3 - Snapshot of the GT-Power® engine 1D model

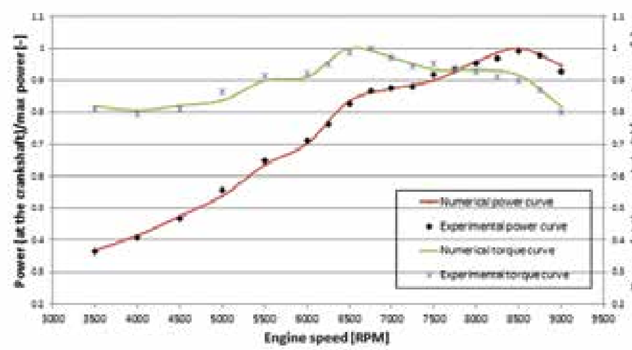


Figure 4 - Engine torque and power curves: comparison between measured and computed

The next step has been to carry out the valve train simulation in the relevant solver node. The specific lumped mass model has been built using GT-VALVETRAIN (the schematic diagram of the valve train analysis model is shown in Figure 5, where a roller rocker arm layout has been evaluated).

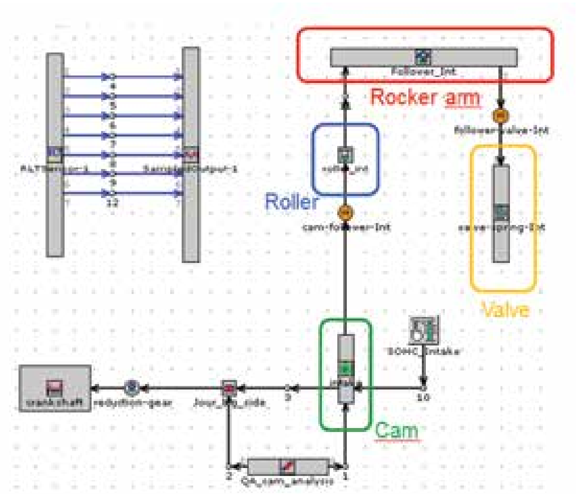


Figure 5 - Snapshot of the GT® valve train model

The graph in Figure 6 shows the good numerical-experimental matching in relation to the dynamic valve displacement at engine over-speed, confirming the good level of prediction of the model.

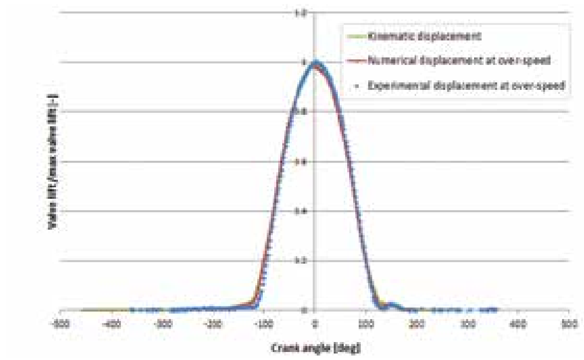


Figure 6 - Valve displacement: kinematic and dynamic profiles: comparison between measured and computed

GT-SUITE and modeFRONTIER have been interfaced by means of the valve lift profile definition. Thus, the parameters of the multiple-polynomial scheme have been the input variables in the modeFRONTIER environment. The output variables controlled during the optimization have been the engine torque and power curves on the one hand, the valve-train kinematic and dynamic characteristic parameters on the other hand.

Logical flow and followed approach during the optimization analysis

The optimization process has been conducted at more levels, involving first a statistical analysis and then a proper optimization analysis.
A pre-statistical analysis has been carried out to check workflow redundancies, to perform a sensitivity analysis and to be able to simplify the following optimization analysis.
The second step consists of a robust optimization for a global search, based on guidelines coming from the previous analysis. Subsequently, it has been possible to select a rank of the top lift profiles based on the valve train and engine performance results. The last step of the project, to address user needs and targets for the specific application and consistency with the computational time, could be a final refined optimization to precisely hit an optimum using an accurate optimizer, for a refinement, starting from the previous global search result. In this work this last step has not been reported, being beyond the scope of this work.

The analysis has focused on minimizing the cam driving torque resistance, maximizing the engine torque at maximum torque speed rotation and maximizing the engine power at maximum power speed rotation. The constraints to be satisfied have been related to the most significant valve train recommendations and guidelines; additionally a target power curve as a lower boundary condition has been considered (this numerical curve has represented the engine performance before to perform the optimization process). Objectives and constraints investigated are shown in the Table 2.

Objectives	Maximize engine torque at max torque speed
	Maximize engine power at max power speed
	Minimize resisting cam torque
Constraints	Total valve lift duration
	Target engine power curve
	Minimum negative cam radius of curvature
	Minimum valve-piston distance
	Normalized valve lift area at max lash
	QDA cam-follower separation speed
	QDA maximum Hertz stress at 0 RPM
	QDA maximum Hertz stress at over-speed
	Valve seating velocity

Table 2 - Objectives and constraints defined in the model

In Figure 7 the optimization process flow-chart implemented on modeFRONTIER is shown.

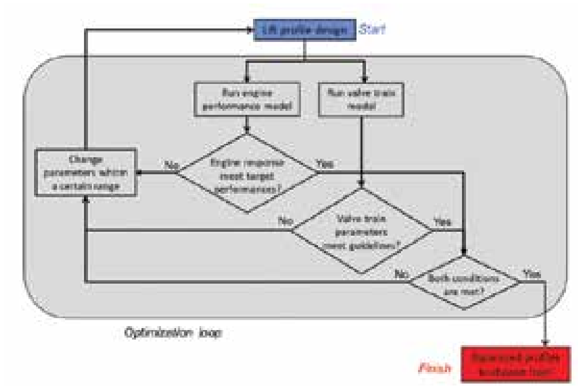


Figure 7 - Optimization flow-chart

According to the flow-chart, the data flow has started from the 10 input variables, whose values define the valve lift event. After the analysis of each design is completed the output values have generated. Once each numerical analysis has performed (running engine performance and valve train models), they have been evaluated by means of suitable instruments for post-processing: the best configurations will be those that meet targets and guidelines chosen.

Statistical analysis

A starting DOE has been selected for the statistical analysis taking care that the set of configurations had to be representative of the whole design space and that the input values had to be not correlated to avoid redundancies.

Cases studied have shown that 3000÷5000 DOE input profiles provide enough resolution to explore the investigated design space. The "DOE Sequence" has been used to determine the general behavior of the examined objective functions.

Table 3 summarizes the number of blocks used in modeFRONTIER model during the statistical analysis.

Number of elements	Quantity
N. input	10
N. constraints (as for the inputs)	1
N. constraints (as for the valve train)	7
N. constraints (as for the engine performance)	1
N. objectives (as for the valve train)	1
N. objectives (as for the engine performance)	2

Table 3 - Number of blocks used in modeFRONTIER model during the statistical analysis

After the DOE table has been evaluated, it has been possible to post-process the results extracting important information about the problem.

Data post-processing has shown there have been some inputs that have interfered insignificantly with outputs variables, while others have affected the output results in a more or less substantial way. This can be seen in the matrix correlation (Figure 8), that illustrates a first order dependency. The correlation value is a normalized index spanning from -1 to +1: a value equal to +1 (-1) denotes a full direct (inverse) correlation, while a low absolute value means low correlation. The same correlation is identified by shades of red (direct) and blue (inverse) color. It has been found that some variables are the least significant input variables and others have been found to affect significantly the results of the analysis (in relation to the ranges defined during the entire process). This is summarized in the Table 4. Finally it has been found that some pairs of objectives or outputs are negatively correlated, that means that such objectives (outputs) are conflicting and thus an optimization strategy should be used to find a good compromise.

During the next step of optimization some design variables will be considered a constant and a more suitable range for other input parameters will be adopted, according to the indications coming from the statistical analysis. As an example, the Parallel coordinates chart (Figure 9) clearly

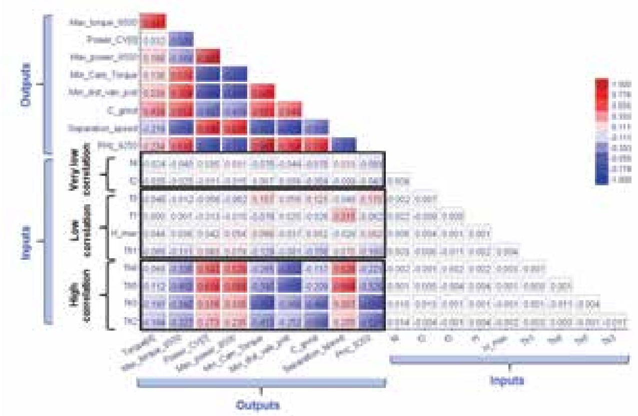


Figure 8 - Correlation matrix chart: relationships between input and output variables

Input variable	How much affects the output
f2	Insignificant
f4	
H_max	Low correlation
θ1	
f1	
f3	
θ2	High correlation
θ3	
θ5	
θ6	

Table 4 - Input variables influence

indicates (applying filters to reduce the ranges defined for the single variables evaluated) how it is possible to make investigations on variables sensitivity. In this type of graph, firstly a set of parallel axes is drawn with the aim to represent each variable, either input or output. Each design is then represented by a single line intersecting each variable axes at the value held by that variable for that design. Since the parallel coordinates chart permits the modification in real time of the range of every single variable, it can be used to filter the most interesting solutions in the database. The Figure 9 shows the convenience to adopt low values for the maximum valve lift profile, in particular to follow the target of reduce the resisting cam torque

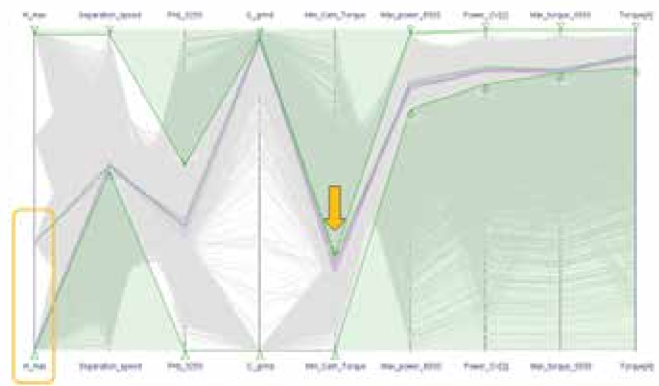


Figure 9 - Parallel coordinates chart (maximum valve lift vs minimization cam driving torque)

Similar considerations have been made using the method based on t-Student distribution, which has once again allowed to see specific relations amongst all the inputs and a single output. This tool adopts both pie chart and histogram representations (Figure 10).

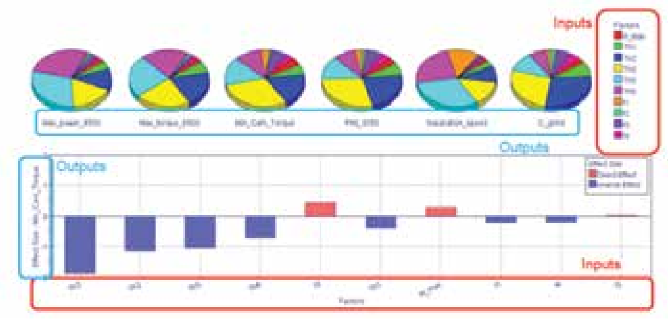


Figure 10 - t-Student distribution charts

Analyzing these charts it is easy to guess that one of the benefits of this procedure is the possibility to understand how each cam design parameter affects the valve train system (in terms of kinematic, quasi-dynamic and dynamic characteristics) and engine performance (torque and power curve). Using this post process data as a sensitivity tool, the cam designer is able to parametrically define the valve lift profile in order to change any output response, conscious that the time is over when the simulation brought good results only after long working experience.

Once the statistical analysis had been carried out, the following stage of the procedure has been aimed at performing an optimization analysis, having the main purpose to define one or more appropriate valve lift events.

Optimization analysis

During the optimization analysis a traditional MOGA II algorithm has been used. This is a multi-objective genetic algorithm. The number of starting population and the number of Generations have been a trade-off focused to increase robustness, accuracy and calculation time. Although the choice to use a genetic (and robust) algorithm, particular care has been taken to provide a DOE able to cover sufficiently the dominium of the functions, so that it can provide multiple starting point for the optimization.

Run times have been reduced launching multiple designs simultaneously. The percentage of feasible designs depends on how strict the constraints are. The conflict between some outputs or objectives negatively correlated has to be considered too. The calculation time also depends on how the problem has been formulated. In this work the choice adopted has been to evaluate unfeasible designs too (from point of view of performance) and to run valve train analysis (the solver node that follows the engine performance node) regardless of the result coming from the performance node. In fact the design constraints have been defined rigidly and therefore it has been preferred to evaluate even the designs not fulfilling all the constraints. Alternatively it would have been possible to include in the optimization model a logic "if" node and redirect the workflow path to the exit node if the performance constraints hadn't been respected.

During this phase the input number has been reduced (from 10 to 7 variables). Additionally a more suitable range for all the input parameters has been adopted.

The optimization analysis has generated a small number of feasible design, demonstrating that the formulation problem has been rather rigid (in terms of design constraints) and highlighting the inverse correlation characterizing the output variables (as shown in the scatter matrix in Figure 11, that confirms the statistical analysis's trends). The scatter matrix chart contains three kinds of information: the Probability Density Function chart

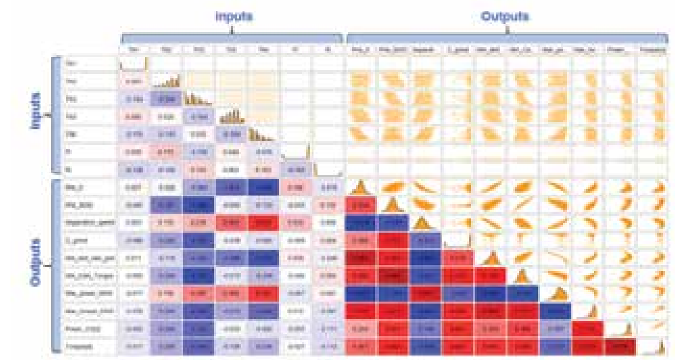


Figure 11 - Scatter matrix chart

for each variable (along the diagonal) , all the pairwise scatter plot (above the diagonal) and the correlation values between the variables (below the diagonal, as described in relation to Figure 8). Despite that, the few feasible designs generated, reached the goal planned during the analysis, respecting settled constraints.
Having more than two objectives, the so-called "Pareto Frontier" (the set of all non-dominated solutions in the search space) is no longer a curve and becomes an hyper-surface. Otherwise the modeFRONTIER's user can use a Bubble chart representation (Figure 12), where the two Cartesian axes represent two objectives and the third is pictured by bubble size. The feasible designs lying on the Pareto Frontier are circled in green in Figure 12.

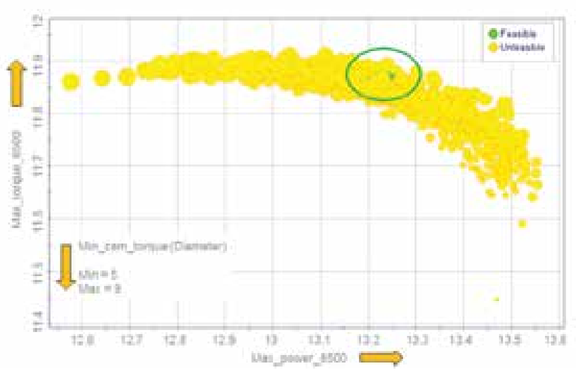


Figure 12 - Bubble chart and Pareto Frontier

The three most promising solutions are highlighted in blue in the Parallel coordinates chart (Figure 13).

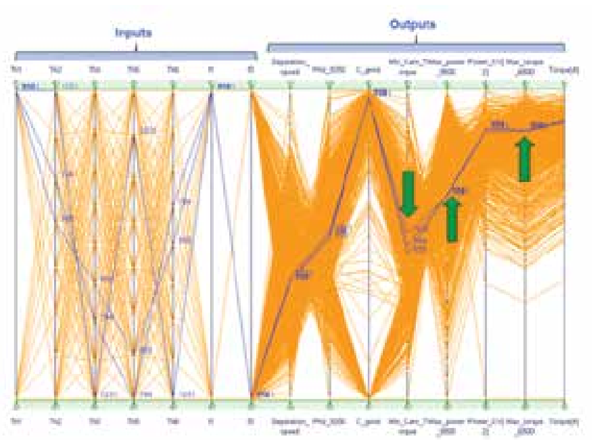


Figure 13 - Parallel coordinates chart showing the three most promising solutions (the arrows point out the objectives to minimize or maximize)

According to the priorities for each objective, an unique final design ID has been selected. The valve lift and acceleration profiles are shown in Figure 14: the comparison between the original and the optimized solution is shown.
The new valve lift has provided the valve train results displayed in Table 5.

The impact on the engine performance in full load condition is depicted in Figure 15: despite the slight worsening at low engine speeds (within the tolerance constraints), the optimized curves display the numerical improvement at the two engine operating conditions considered, in particular at high regimes. The slight improvement is clearly due to the problem formulation, where many objectives and design constraints

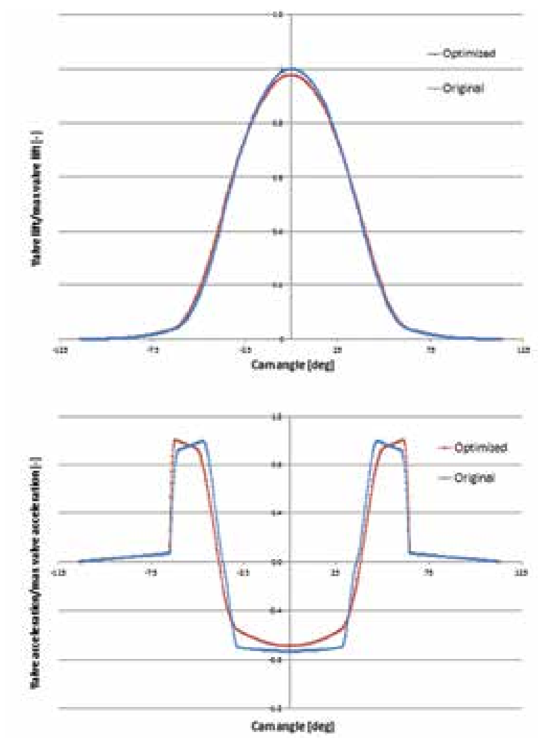


Figure 14 - Valve lift and acceleration profiles: comparison between the original and the optimized solution

overlap reciprocally. The multi-objective approach permits the analyst to assign a priority to each objective or constraint; making the thermodynamic objective the top-priority one could have been another way to go (to the detriment of the valve-train aspects).
The entire optimization procedure has been exploited both for the intake and the exhaust valve lift (this last analysis has not been reported, being beyond the scope of this paper). The graph in Figure 15 takes account of both optimized diagrams.
As shown above the effects on gas exchange have not involved any significant variation in engine performance.

Valve train characteristics	Improvement %	Meet guidelines
Min negative cam radius of curvature (opening flank)	/	Yes
Min negative cam radius of curvature (closing flank)	/	Yes
Min valve-piston distance	-10%	Yes
Normalized valve lift area at max lash (excluding lash zones)	2%	/
Cam-follower separation speed	15%	/
Peak cam torque at overspeed	-20%	/
Max Hertz stress at zero RPM	-1%	Yes
Max Hertz stress at overspeed	-2%	Yes
Valve seating velocity (reported at 0.1 mm of valve lift)	-10%	Yes

Table 5 - Optimized valve train characteristics

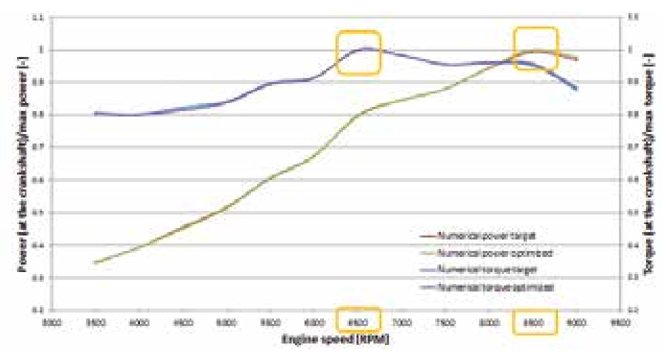


Figure 15 - Engine indicated torque and power curve: comparison between original and optimized solution (highlighted the engine speeds most significant for the analysis)

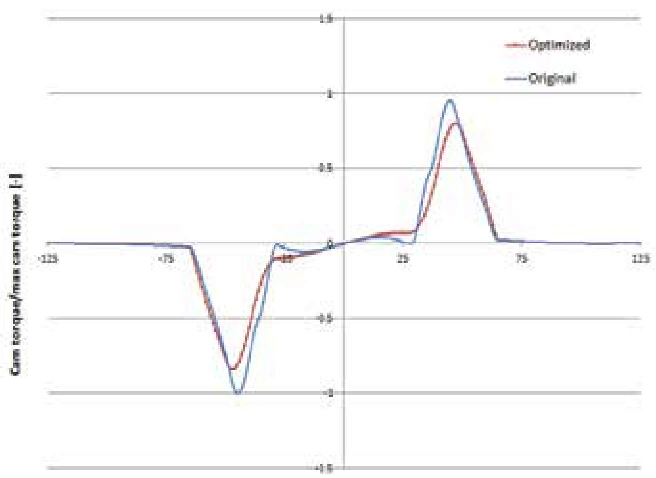


Figure 16 - Cam torque: comparison between original and optimized solution

The graph in Figure 16 shows the improvement in resisting cam torque and therefore in friction reduction, between the original and the optimized curve at over-speed. The original data refers to the cam design initially adopted for the 4-valves engine, before the exploitation of the current methodology.
As a result of the new optimized valve lift event it has been possible to modify the valve spring characteristics (Figure 17), using a new spring setup with lower loads and mass, in order to reduce the frictions. The original data refers again to valve spring configuration used prior to the optimization analysis.

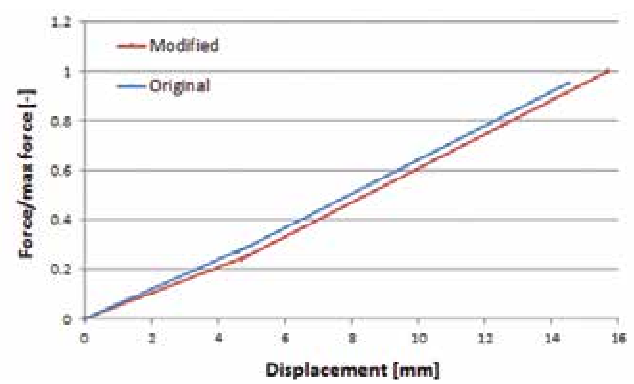


Figure 17 - Valve spring characteristics: comparison between original and modified solution

In this project the optimization procedure for the intake valve lift event has been described. The same approach has then been used and applied for the exhaust valve lift (as mentioned earlier this last analysis has not been reported, being beyond the scope of the present work). The whole valve train system has benefitted from this optimization procedure, involving a new valve spring setup and a new cam design. These changes have allowed the improvement of the engine friction as well as stability and durability issues due to the decreased stress; the engine performance has slightly improved without any significant variation.

Conclusions

With market pressure to decrease the environmental impact of new engines and with increasing software reliability, it's imperative to find new efficient methods to improve exiting solutions by numerical optimization approaches. The idea at the basis of the paper has been to build a numerical tool for the valve lift profile definition, focusing on valve train system working and on engine performance. Thus, it becomes possible to have a new robust methodology to test effectively and efficiently valve lift solutions. In this work modeFRONTIER has been used to perform a multi-objective optimization. The multi-polynomial valve lift has been the starting point to drive the integrated procedure in optimizing the cam definition with a view to the valve train behavior and to the engine performance. The optimized profile has been found with the use of genetic algorithm tools. Therefore an integrated approach between the modeFRONTIER platform and the GT-SUITE numerical code has been performed in order to build a methodology to define the valve lift event and to give support to the analyst during the design of a cam profile.
This work has focused on the valve train system, because it is an integral part of any engine and is closely related to the flow efficiency, the performance of the engine and impacts on high durability and low frictions of the timing system.

Firstly, a statistical analysis has been performed that has sped up the optimization phase by reducing the complexity of the problem, limiting the number of variables and the variables definition range. The subsequent optimization problem has therefore been used to improve the timing system lift event, in terms of the valve train system's dynamic characteristics and thermodynamic performance requirements. Particular care has been taken to verify some important characteristics, like the engine power and torque, the resisting camshaft torque, the cam-follower separation speed, the Hertz stress, etc.
This approach has allowed the simultaneous modification of both the valve springs set-up and the cam profile shapes, in order to obtain the required response as for the engine friction reduction; furthermore the whole timing system has benefitted from this procedure, improving stability and durability issues.
To conclude, this project demonstrates the use of state of the art simulation tools and their correct implementation into the development process. It also highlights the great benefit of such a process in the development of Piaggio's new small 4 valve scooter engines.

Francesco Maiani, Piaggio & C. s.p.a.
Marco Serafini, EnginSoft

modeFRONTIER bolsters Henniges Automotive's seal performance

In recent times, car sealing systems design has seen major technological advances in both materials and manufacturing techniques. Getting the design just right involves satisfying a multitude of specifications and dealing with factors that impact performance and, most importantly, requires close collaboration between the manufacturer and the customer. Henniges Automotive, a leader in vehicle sealing and anti-vibration solutions, has technical centers in North America, Europe and China that cater specifically to regional requirements.

Challenge
Seal design must take into account various customer specifications such as low door closing effort, easy part installation, secure part retention, low glass seal drag and much more, while at the same time, satisfying both short and long-term sealing performance. Moreover, engineers need to optimize seal design to ensure robust performance under vehicle sheet metal variation as well as variations in material and geometry that occur in the rubber manufacturing process.

Solution
Through the successful integration of MSC MARC and Altair HyperMesh in the modeFRONTIER workflow, Henniges engineers were able to automate the simulation of seal behavior with different geometry configurations. In just two days, more than 1600 design configurations were analyzed by modifying 13 grip fin variables including length, thickness, angle and location (Figure 1).
"Thanks to modeFRONTIER we could consider a large amount of possibilities; an impressive result for our customers", says Ken Ogilvie, CAE Manager. More importantly, modeFRONTIER provides Henniges engineers with the necessary tools to go through the hundreds, even thousands, of designs to find not only better but also more robust solutions.

Thanks to modeFRONTIER we could consider a large amount of possibilities; an impressive result for our customers

modeFRONTIER Advantages
"It's difficult to make a part exactly to client specifications due to the variability in the rubber extrusion and molding process. Robustness therefore becomes very important when designing automotive seals. That's why we choose modeFRONTIER; for its optimization and robustness capabilities," says Fan Sheng, CAE Technical Specialist at Henniges. Looking to the future, Ogilvie says "modeFRONTIER helps us make significant improvements in the quality of our designs; without modeFRONTIER, it's just trial and error based on past experience."

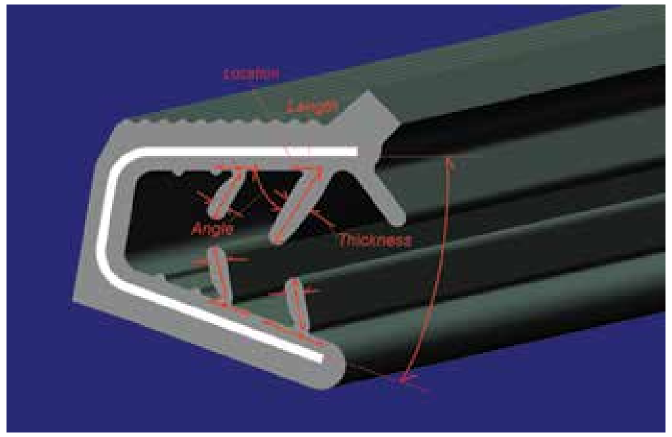


Figure 1 - Seal geometry

...we choose modeFRONTIER for its optimization and robustness analysis capabilities

About Henniges Automotive
Henniges Automotive provides world-class vehicle sealing and anti-vibration solutions for the global automotive industry. Since its inception in 2007, Henniges has been committed to its strategy of flawless execution – driving innovative solutions for its customers through flexibility, agility and transparency. Headquartered in Auburn Hills, Michigan, Henniges utilizes the talents of associates located in six countries and across three continents to meet customers' growing global needs.
www.hennigesautomotive.com

ESTECO North America
ESTECO North America (NA) is a direct subsidiary of ESTECO spa (Italy). ESTECO NA opened in 2004 and is primarily responsible for business development and customer success in North America. The majority of the employees play a role in the technical team to stay engaged with the customers for application, support, consulting and training. Customers include companies from the automotive, aerospace and appliance manufacturing industries. Examples include: Ford, Cummins and Whirlpool. The North American branch has contributed to the successful growth of ESTECO's products through distributors in the region as well as provided strategic guidance to the Italian headquarters for the overall success of ESTECO's products and business worldwide.

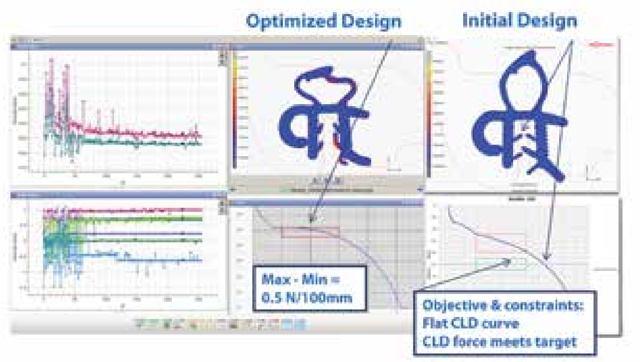


Figure 2 - Baseline and optimized designs - modeFRONTIER Run Analysis

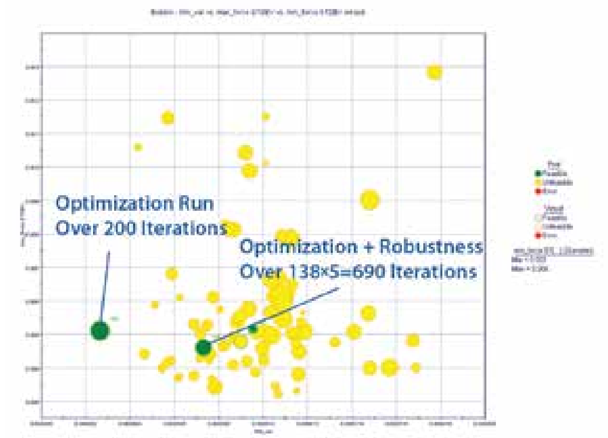


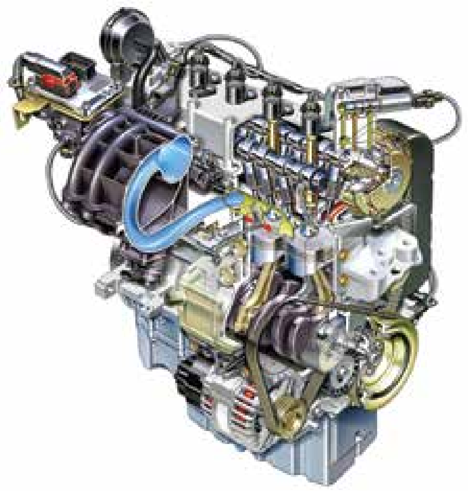
Figure 3 - modeFRONTIER Pareto Bubble Chart - Robust Optimization

modeFRONTIER in the Automotive sector

modeFRONTIER can be used in all industrial sectors and in particular, as far as the automotive application is concerned, it can provide notable results for multi-objective simulation activities related to:

- Optimization of pre-design automotive systems;
- Cooling system and HVAC system;
- Aerodynamics Optimization;
- Multibody analysis and optimization;
- Dynamic analysis and optimization;
- Safety system.

CRF: Excellence Centre for Research, Development and Innovation



Centro Ricerche Fiat (CRF) is a private company engaged in research and development and centre of excellence in the automotive sector. CRF, dealing with the promotion, development and transfer of innovation, was founded in 1976 as a reference point for all those research and development services dedicated to Fiat Group companies. CRF objectives are focused on innovation, as strategic lever, and exploitation of the results coming out of its activities, by means of promotion, development and innovative knowledge transfer, able to make products competitive and distinguishable.

CRF develops efficient and creative solutions at competitive costs, thus favouring the technological transfer also through the training of qualified personnel. In this way, it actively supports the technological growth of Fiat Group, its partners and the territory in the automotive sector, its components, energy, environmental-friendly and safe mobility, telematics, new materials and related technologies, mechatronics, optics. CRF has 4 branch offices (Bari, Catania, Trento and Foggia), a controlled company (Udine) and has reached 2100 registered patents, more than 900 pending petitions and 128 projects won in the Six Framework Program for European Research.

The choice of modeFRONTIER is not only related to technical evaluations, even if they are extremely important and allowing this innovative Italian technology to be adopted by CRF and also by other several automotive OEM around the world. As far CRF is concerned, two further aspects are very important. First, the software users can have a direct contact with modeFRONTIER developers, which is very rare in the software global market. Second, this condition has allowed the developers to improve some new features, verifying them on application case of industrial complexity (i.e the integration node of modeFRONTIER with UG NX™ and Abaqus™)

Why modeFRONTIER at Centro Ricerche Fiat

In such situation, the efficient use of the most diversified CAE (Computer Aided Engineering) tools, also thanks to forefront multi-objective optimization techniques, can play a fundamental role and make the difference. Considering the infinite variables of a project, and the consequences related to wrong decisions, it is extremely important to have a tool able to integrate and complement all available resources, allowing the working team to concentrate on real goals and to reach even unexpected results.

Such software would require unique features for ambitious targets: to be robust and totally independent of the hardware platform, including multi-objective optimization algorithms, and to include interactive tools supporting the decision-making process. modeFRONTIER gathers all these characteristics and can be used in the most heterogeneous applications, from air conditioning to structural reliability. In this last specific context, modeFRONTIER has been used in CRF from the preliminary stages of a new architecture for a vehicle body, till the detailed optimization and final virtual test, so to make the structural design of a new car evolving in the best possible way.

Landi Renzo: the global leader for components, LPG and CNG fuel systems

Based in Cavriago (Reggio Emilia - Italy), with more than 50 years experience in the sector, Landi Renzo is distinguished by a sustained revenue growth, a listing in the STAR segment of the Italian stock exchange, and the extent of its international operations, with a presence in over 50 countries.

The Landi Renzo Company was established in 1954 when Renzo Landi and his wife Giovannina Domenichini founded Officine Meccaniche Renzo Landi, at the time the only manufacturer of mixers specifically designed for all kinds of vehicles.

Landi Renzo S.p.A. is now a global leader in the sector of components and LPG and CNG fuel systems for motor vehicles, serving more than 30% of the market of alternative automotive fuel systems and components. It is a preferred supplier by a growing number of worldwide brands like Daimler Chrysler, Fiat, Opel, PSA, Renault, Volkswagen, and more recently Toyota. Landi Renzo S.p.A. Research and Development Centre is currently the only one in its field to use advanced technologies that allow creating and developing modern systems to convert vehicle fuel systems to LPG and CNG.

modeFRONTIER in Landi Renzo

"The first project with modeFRONTIER, dates back to 2008, when we performed an optimization of the new Electronic Pressure Regulator (EPR) - says Ferdinando Ciardiello, Research & Development Modelling Manager at Landi. "Ercole Sangregorio, current EPR Project Manager, - continues Ciardello - built-up a two steps development: at first, leveraging on experimental test data available in our in-house facilities, modeFRONTIER calibrated a numerical model of the EPR. We obtained a very precise 1D model, able to predict well and quickly the system's behavior, the steady-state and the transient in different possible configurations. Afterwards, modeFRONTIER was used as a process integrator and a multi-objective optimizer, connecting different software tools to build a truly and multi-disciplinary virtual bench, with mechanical, pneumatic and control system models, and finding overall optimal configurations. In this way, we were able to minimize pressure oscillations in the control volume and to get an optimal and robust EPR configuration in just few weeks". "Moreover, we expanded the concept to 3D fluid-dynamics design, particularly with the ANSYS Workbench direct node in modeFRONTIER, resulting in scheduled 3D simulation campaigns during night time and weekends. It proved to be a very efficient approach, based on the state-of-the-art Design Of Experiment available in modeFRONTIER."

Computer-Aided Engineering has always been a key success factor for our growth and EnginSoft has been supporting our demands well for years. Adding modeFRONTIER to our software chain has been a winning move for more than one reason: with modeFRONTIER our approach to product concept has become more systematic and now allows us to evaluate more alternatives and take into account the effects of more design variables. This translates into value to our customers: critical factors are understood and handled much earlier in the process and the design results more robust in a shorter time. modeFRONTIER has also improved the predictive power of our numerical models by feeding them with lab testing results. This philosophy has reduced development times and costs, and our team can cater to customer demands and discuss specifications with them more efficiently.

Ercole Sangregorio
Leader of the Components Division
Landi Renzo

Effective Decision Making for Many-Objective Problems using Advanced Multi-Variate Data Analysis

Saket Kansara - Technical Manager at ESTECO Software India - explains how to adopt effectively MVA methodologies to reduce optimization problem complexity and streamline the decision making process when dealing with large numbers of variables and objectives. Collecting from his direct experience with customers, Saket presents the benefits and the best approach to MVA techniques such as Clustering and PCA.
Saket was the first technical team member for ESTECO's India office and is primarily responsible for technical activities for Indian subcontinent but also helps ESTECO to support some global customers from Australia to Europe. Before starting ESTECO operations in India he worked for the Multi-Disciplinary Optimization (MDO) team at FORD Motor Company. He completed his MS in engineering from State University of New York (SUNY) at Buffalo, with specialization in engineering optimization.

1. What are the challenges faced by designers when selecting the final design?

Decision making in engineering design is complicated, especially when dealing with high-dimensional data. It is becoming common to see problem setup with hundreds of input parameters, many objective functions and constraints. Modern design tools are able to produce a large amount of data while performing optimization studies, especially thanks to the advancement in the software technology and the computational resources available. In fact it is becoming a real challenge to analyze such large data sets and then make effective decisions. Additionally when dealing with multiple objectives of conflicting nature the decision process becomes quite difficult to handle with a "manual" approach. While Pareto frontier solutions for a two or three objective space are easy to visualize and comprehend when it comes to 100s or even 1000s Pareto Optimal solutions obtained from an optimization study, analysts can be overwhelmed by such amount of data.

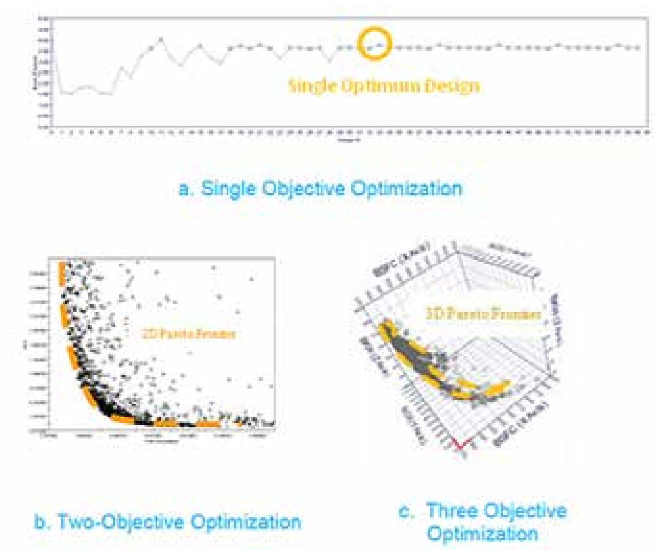


Figure 1 - Results from One, Two and Three Objective Optimization

2. What techniques do you consider effective in supporting engineers in the decision-making process?

Multi-Variate data Analysis (MVA) methods, such as Clustering, Principal Components Analysis, Self Organizing Maps and Multi-Dimensional Scaling, have been in use in many data analysis fields, for example economics and social sciences, because it helps you analyze data with many variables simultaneously and identify patterns and relationships. The use of these methods in engineering design is quite new, but has already proved to have a huge potential. All these techniques are available in modeFRONTIER together with a number of dedicated charts, which further simplifies the engineer's job. For instance, clustering can help you isolate groups of designs with similar properties, exclude those with insufficient performance and thus considerably reduce the amount of data to be considered. Partitive Clustering is one of the simplest and most efficient unsupervised clustering methods. The algorithm treats each data item as an object having a location in space. It finds thus a partition in which items within each cluster are as close to each other as possible, and as far from objects in other clusters as possible. The Principal Components analysis transforms high-dimensional data in a lower-dimensional form without losing too much information and eliminating correlations between variables. It helps identify patterns and spot similarities and differences which would otherwise remain unnoticed.

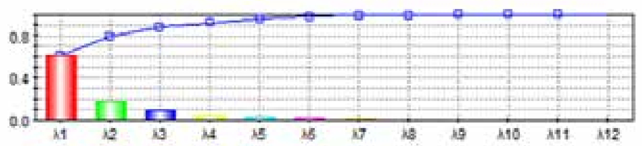


Figure 2 - Amount of variation explained by each principal component

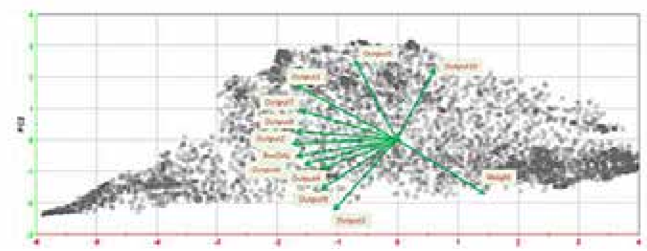


Figure 3 - Example of data plotted in first two principal components

3. Can you provide some detail on how these techniques work?

These techniques are particularly useful when applied to the huge amount of data we usually obtain as a result of a modeFRONTIER optimization and we need to make sense of these data. PCA uses an orthogonal transformation which reduces the dimensionality of a dataset containing a large number of possibly correlated variables. Principal components are orthogonal uncorrelated artificial variables representing the original dataset and accounting for most of the variance present in the original variables.

The first principal component accounts for as much of the variability in the data as possible, whereas the second component accounts for the highest possible variance in the original data that was not included in the first component. The remaining components have the same characteristics. The results of a PCA are usually discussed in terms of component scores and loadings. Loadings measure the importance of each variable in the variability of a principal component. High correlation between PC1 and a variable indicates that the variable is associated with the direction of the maximum amount of variation in the dataset. On the other hand, if a variable does not correlate to any PC, or correlates only with the last PC(s), this usually suggests that the variable has little or no contribution to the variation in the dataset. Therefore, PCA may often indicate which variables are important and which ones may be of little consequence. Some of these low-performance variables might therefore be removed from consideration in order to simplify the overall analysis.
Partitive Clustering decomposes a dataset into a set of disjoint clusters, the number of which must be defined by the designer, which is basically the main difficulty in applying this technique. The algorithm obeys two rules: each cluster must contain at least one point and each point must belong to one cluster only. The clustering criterion is the Euclidean distance between each design and its nearest cluster center, called centroid. The preliminary group is formed by assigning each design to its nearest centroid, and the centroids are then recalculated a moved to become the barycenters of the clusters. In the next iteration designs are reassigned to the nearest centroid, which may also belong to a different cluster. This process is repeated until the sum of distances between each design and its centroid cannot be further decreased, i.e. the centroids do not shift by more than a given threshold.

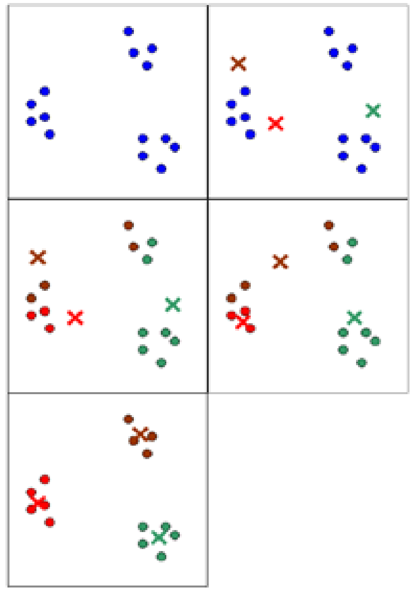


Figure 4 - Partitive Clustering step by step

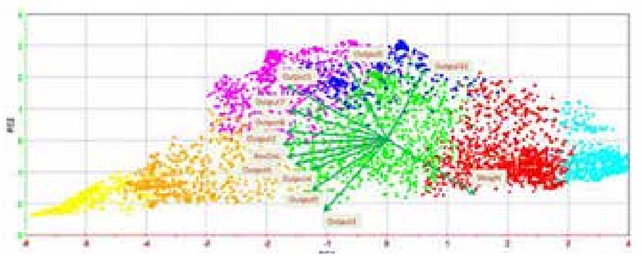


Figure 5 - Dimensional Scatter chart with different dimensional data plotted in two dimensions with colors showing clusters obtained from clustering analysis

4. Can you give us a practical example in which Clustering and PCA helped take the right decision?

Some good insights can be grasped from a recent study we have done. It was a common rail fuel injector optimization problem that we tackled using the modeFRONTIER software. The fuel injector 1D representation was developed with Gamma Technologies software to simulate its behaviour and the problem consisted of five objectives, namely minimize open time, minimize close time, maximize sac pressure, minimize leakage and minimize voltage difference. The Pareto frontier obtained had 156 designs and it was clear that analyzing trade-offs with respect to 5 objectives among as many candidate solutions would have been quite tricky without having very clearly defined preferences. Hence our target was to reduce the number of candidates to five or six representative designs covering the entire Pareto frontier spread to make the task more easy to manage. First of all we performed a correlation analysis the dataset, to understand the correlation patterns between variables. Since we are only interested to explore trade-off in multi-objective solution space, this step clearly showed where the redundancy was in the performance space representation, allowing for the data to be represented in less than five dimension. Even though the clustering and PCA approach can work in isolation without each other's help, choosing designs with only one of these approaches can become confusing as one is never quite sure how far away the designs are from each other. For example, if designs are chosen using clustering analysis only, it is possible that these designs are very close to each other even though they belong to different clusters. If designs are chosen using PCA study alone, one is never quite sure if they belong to the same cluster or not. Using PCA and Clustering together can help overcome this issue and provide better clarity in decision making.
We used the combined approach and the resulting plot showed the results of the clustering analysis by means of different colors while the position of the data points came from the PCA. Now it's straightforward: if the same colored designs, i.e designs belonging to the same cluster, are close to each other in the chart, it indicates that the clustering analysis and PCA are complying with each other's results. Choosing designs becomes then simpler as one can select one design belonging to each cluster and located far from each other on the scatter chart.

ESTECO India

ESTECO Software India Pvt Ltd, a direct subsidiary of ESTECO spa and ESTECO North America, is primarily responsible for business development and customer success in South Asia. The team in India works closely with ESTECO North America and ESTECO Spa (Italy). Along with business development, it also provides application, support and training services to local and global customers as well as software testing and development services for ESTECO's products. Customers include domestic Indian companies like TATA, Bajaj as well as global companies like Ford, Cummins and Whirlpool.

Structural Optimization of a Car-body High Speed Train
An Innovative Analysis and Design Methodology

In the past, the main challenge was to achieve a very high speed, but today the criteria such as energy efficiency, high transport capacity, comfort and low environmental impact are becoming more and more important. For this reason the philosophy of AnsaldoBreda is to combine a settled design process with innovative approaches to optimize the reliability, safety, low power consumption and an easy maintenance. In order to be competitive in the market, especially in this economically challenging period, it is necessary to push the envelope of the available technologies to ensure compliance with top level quality standards.

AnsaldoBreda
A Finmeccanica Company

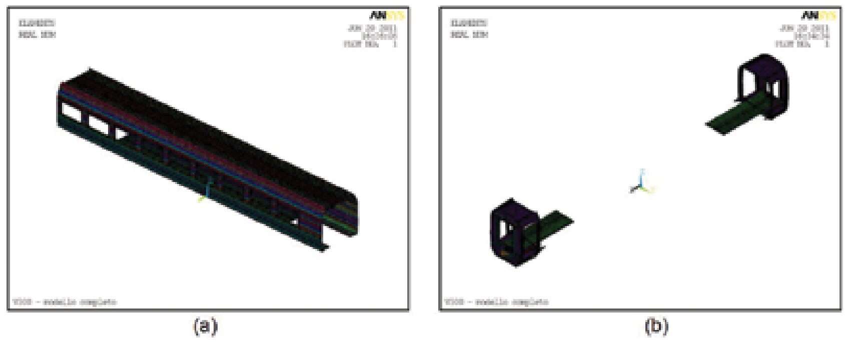


Figure 1a - Fuselage Parametric part of high speed train: it has been completely development in ANSYS APDL
Figure 1b - No -parametric part of high speed train: terminal tapered parts are fixed geometry

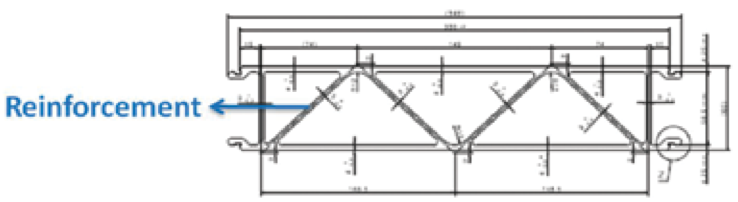


Figure 2 - Section profile of carbody

A new methodology approach has been developed by exploiting the new capabilities of the multi-objective design environment modeFRONTIER and it has been applied to the design of the carbody structure of a new generation of High Speed trains. In this context, the aim of the activity was the design optimization of the aluminum carbody structure in terms of weight and dynamic behavior, respecting all project constraints according to the high standard structural and crash requirements of European EN 12663 - Category P-II (Fixed units) and TSI Rolling Stock.

Starting from the CAD model of the original configuration, the FE comprehensive parametric model has been developed by ANSYS APDL procedure and integrated into the modeFRONTIER optimization platform to achieve the requested goals. The FE parametric model has been divided into two different main parts:

1. The central parts of the carbody (named "fuselage") – as shown in fig.1a.
2. The terminal tapered parts of the carbody – as shown in fig.1b.

The fuselage geometry (fig.2) is completely parametric in terms of:

a) number of the profile reinforcements;
b) angle, position of reinforcements;
c) thickness of reinforcements;
d) thickness of external and internal skin of profiles.

The aims of the optimization process of a carbody in modeFRONTIER are:

a. Minimizing weight
b. Maximizing two first own frequencies

with the following constraints:

a. Max Von-Mises stress for static analysis
b. Max Von-Mises stress for equivalent crash analysis
c. Max Von-Mises stress for fatigue analysis
d. Min buckling factor for linear instability analysis

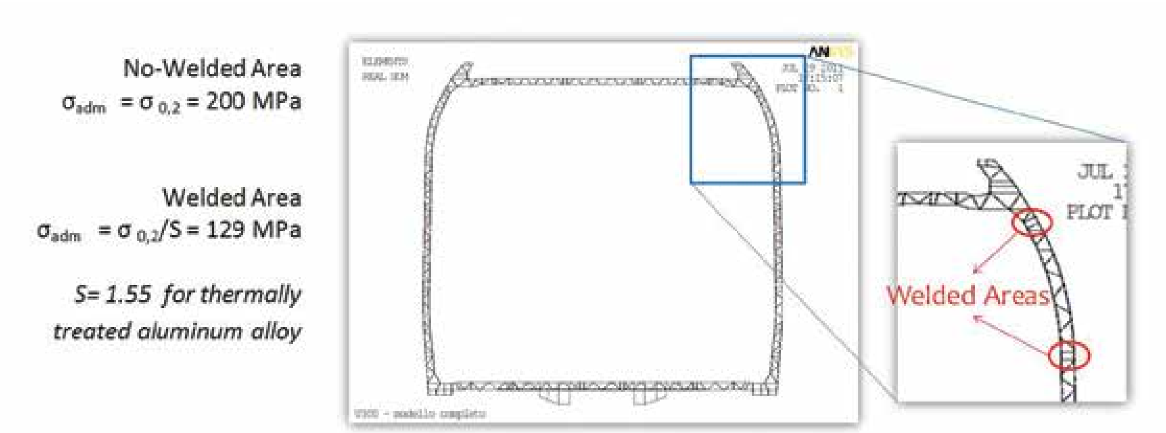


Figure 3 - Section of a carbody structure

The original configuration, only referred to the parametric part of the carbody, weighs 5.927 Tons. The main goal is the weight reduction by min. 500 Kg, maintaining the first bending frequency of 11 Hz.

The static structural analysis and fatigue analysis have been performed for both welded and unwelded region (fig.3), which have different material features:

Due to the high number of time-consuming simulation and the high number of input variables, a progressive approach has been studied for the optimization analysis.

Therefore, the optimization analysis has been carried out in three steps:

- Step1: Screening, driving towards the best designs region;
- Step2: Rough refinement, including the most important constraint conditions;
- Step3: Final refinement, achieving the optimal solutions.

A total of 23 different working -load cases have been considered, with an additional specific comfort requirement about Static Pressure load (-8 KPa inside Tunnel) which constrained the side walls displacements (Uy < 3mm and Uz < 4.5 mm)

The whole simulation took 3 weeks on cluster machine with 8 parallel simulation (32 core).

The first optimization step has been carried out taking into account the two most important objectives of the problem (increase of frequency and weight reduction) which lead the designs to the best region and allows to reduce the design space of the input variables. Only the modal analysis has been performed to find out the best region for weight and frequency with no time-consuming run (less than 1 hour on the cluster machine).

The results of this first optimization loop has been used as a starting DOE (Design of Experiment) for the second one, where objectives/constraints related to displacement under pressure loads and to the 5-6 strongest load cases (fig. 4) have been introduced. This step is more time-consuming than the first one (5 hours on the cluster machine).

After these optimization loops, some variables have been changed in agreement with AnsaldoBreda, and the final optimization run has been done to achieve the best solutions. Since this step was really time-consuming (15 hours on the cluster), the problem has become to mono-objective: only the weight has been considered, while the other objective has become constraints (fig. 5). The set of best designs belonging to the new Pareto frontier has been verified

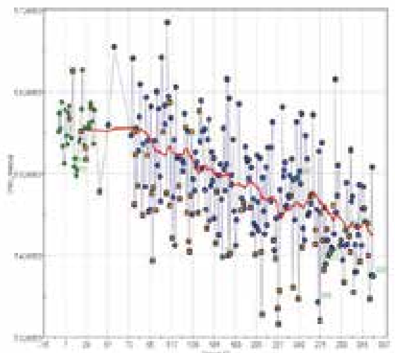


Figure 4a - History of weight convergence (green points: 1st optimization loop; blue points: 2nd optimization loop).

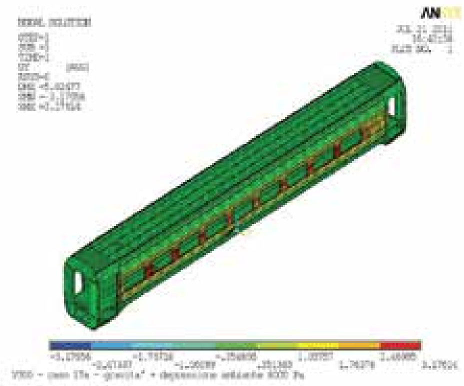


Figure 4b - displacements in y direction (mm)

for each operative load condition and the best designs have been chosen using decision making tools.
The optimal designs selected on the basis of stress and weight values have a considerable variation of both external and internal skin thickness, which can cause manufacturing problems. In order to avoid such problems, another post processing analysis has been done to find out Pareto solutions with a homogeneous distribution of thickness along external and internal skin. New post processing using "parallel chart" applied on best design has been carried out in order to find a suitable solution matching the new requirements introduced a-posteriori (fig. 6). Table II shows the comparison between the best design selected at the end of the optimization analysis (Design ID 378) and the best design after the last post processing considering a thickness uniformity (Design ID 339).
Thanks to the implemented methodology and the optimization routine, a considerable weight reduction has been reached. The chosen solution, Design ID 339, has a weight reduction of 546 Kg (- 9.2%) and it has a more uniform thickness variation which simplifies the carbody manufacturing.
This work aims to shows how to exploit new design methodologies and new technologies in order to manage industrial design processes that involve a large number of variables (more than 50), several constraints and objectives, finding the best solution according to industrial timing.
It is possible to summarize the most important steps of this activity, as follows:

- The design optimization procedure developed has been completely automated: this allowed to make the most of all available hardware and software resources, completely exploiting the downtime (nights and holidays).
- The requested weight reduction has been achieved respecting every structural and comfort requirements: this has totally fulfilled the expectations of the modeFRONTIER industrial users.
- The additional requirement about manufacturing has been fulfilled without re-run any analysis thanks to the new methodology approach: this has been possible thanks to the really powerful capabilities of the post-processing tools of modeFRONTIER.
- The optimization methodology can be completely re-used for other design processes: this activity was dedicated to a specific carbody but this approach can be easily adapted also to other railway vehicles.

Francesco Franchini - EnginSoft

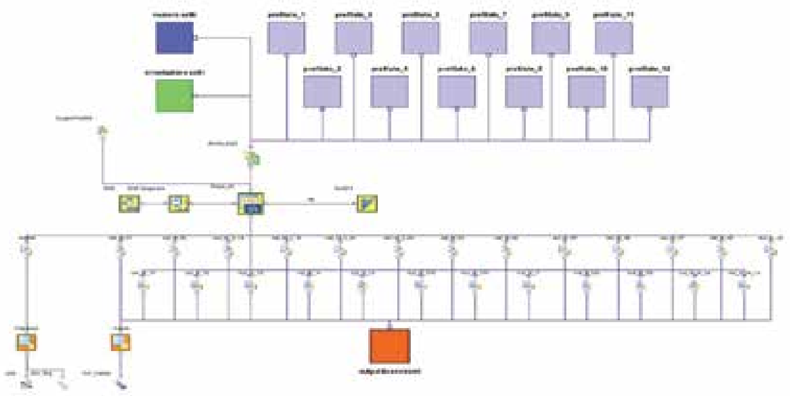


Figure 5 - The workflow of modeFRONTIER with all input and output variables, the final objective and constraints

	DOE	Optimization Scheduler	Total Designs	Lower weight achieved
Step 1	Random : 52 designs	MOGA-II, 12 generations	624	5.535 tons
Step 2	Previous Pareto + Incremental Space filler : 47 designs	MOGA-II, 8 generations	376	5.414 tons
Step 3	Last Pareto	Mixed: MOGA-II + Simplex	112	5.377 tons

Table I - The table above summarize the optimization strategy adopted. The total number of design has been run in 20 days

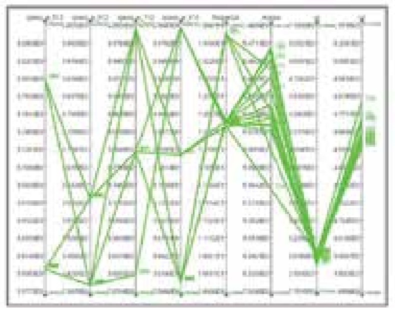


Figure 6a - Parallel chart of the best designs

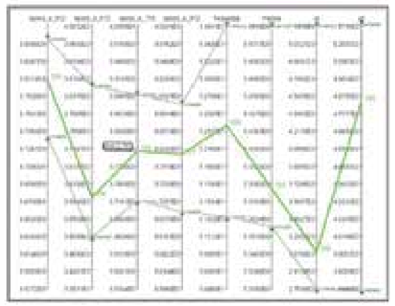


Figure 6b - The selected design (Design ID 339) with homogeneous thicknesses

Design ID	Mass [tons]	Δmass [Kg]	Uy [mm]	Uz[mm]	Frequency [Hz]
Original	5.927	-	> 3.5	> 4.5	< 11.0
378	5.377	-550	3.04	4.32	> 11.5
339	5.381	-546	3.09	4.85	> 11.5

Table II - comparison between the original solutions and the optimized solutions

<ID>	spess_e_512	spess_e_612	spess_e_712	spess_e_812
378	3.8	3	4.6	3.4
339	3.8	3.6	3.8	3.8

Table III - Thickness comparison of the side walls of fuselage (profile ref. 5-6-7-8)

Optimization of a windshield structure

The present work deals with the activities that DEMA SpA is doing for a new Canadian business jet. The company, based in Naples, is responsible for the design and manufacture of the canopy, windshield and nose landing gear box structure as well as the pilot and transition floors. The current activity is focused on the investigation of the windshield stress field due to a static load, and with respect to different thicknesses of composite frames. The main goal was to assess the capabilities of a methodology for the smart analysis of the windshield structural behavior by using a FE (Finite Element) model integrated with modeFRONTIER. A key point of the whole activity was not only to perform a multi-objective optimization, but also to obtain a deep insight into the investigated phenomena. Further, an essential requirement of the methodology was to ensure that it could be efficiently integrated into the flow of company's processes.

Contents

The Windshield structure is a part of the cockpit of an aircraft; the structure is designed by means of static and fatigue stress (Von Mises or Max Principal Stress) coming from Global Finite Element Model (GFEM). The object was to delineate a methodology which would be able to automatically and intelligently change the thickness of GFEM shell elements, run the new numerical analysis and finally obtain a configuration with a minimum mass target, but at the same time able to stay within a well-established threshold stress. The investigation was further developed to identify the best trade-offs between mass and stress minimization, enabling the selection of a wider range of potentially suitable configurations.

The Global FEM

The Global FEM was developed with MSC Nastran code and comprised 2D shell elements of different properties, each one possessing its own thickness; the variation in thickness determining the variation of mass and strength. At the beginning the number of properties was 16 (i.e. we had 16 thicknesses, each labeled with 'ps_<id_shell>'). The maximum value of Von Mises Stress was required to be less than 64000 ksi.
The critical Load Condition was the differential pressure 2DP (29 psi) and was uniformly distributed on the skin and on the inner side of machined parts. With respect to the baseline configuration (design 0), the GFEM was characterized by the thicknesses given in Table 1, whilst the corresponding mass and strength (in terms of max of Von Mises stress) were respectively 111.13 lbs and 101295 ksi.

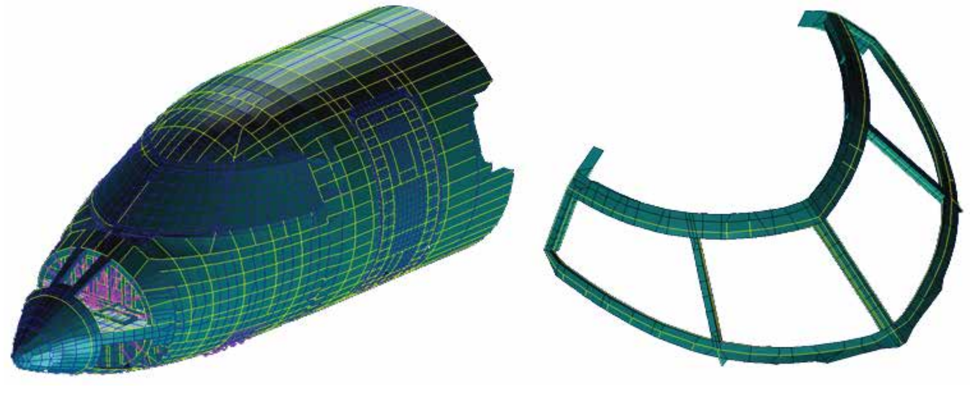


Figure 1 - GFEM: the finite element model of the Cockpit and the windshield alone

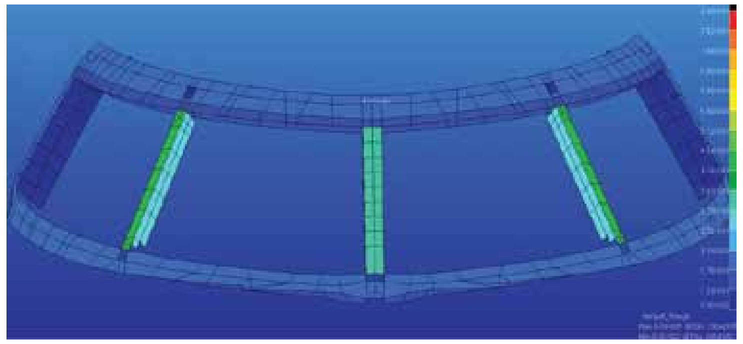


Figure 2 - Windshield GFEM properties distribution

Methodology Implementation in modeFRONTIER

The methodology which was developed relied on the modeFRONTIER workflow depicted in Figure 3, representing both a data and a logical flow. The workflow is able to describe both the method by which the phenomena may be investigated and also to manage the analysis strategy (e.g. the initial DOE and the subsequent optimization algorithm). The design parameters were as follows:

- input variables → 16 thicknesses
- output variables → total mass, maximum of Von Mises strength
- objective function + constraint → total mass minimization + maximum Von Mises strength less than the allowable (<64000 ksi). The Von Mises value was further subject to an objective function with the aim of obtaining the best trade-off between mass and stress minimization.

Every element of the workflow was provided by a so-called "node". The data flow began from the 16 input variables, whose values were updated in the Nastran model, and after the analysis of each design was completed the 2 output values were generated. This process was iterated repeatedly under the control of the initial DOE, followed by the optimization algorithm. Central to this process were two "batch" nodes, the first of which ran the Nastran analysis, and the last of which executed the Patran code for post-processing. The post-processing was built upon a Patran ".ses" macro file obtained from a manual initial post-processing trial. The building up of modeFRONTIER workflow allowed the analyst to perform the optimization process in a very easy and flexible way.

Input Variables	Value
dummy	1.0000E0
ps_200	2.0000E-1
ps_201	3.3000E-1
ps_210	1.5000E-1
ps_211	1.5000E-1
ps_212	2.1000E-1
ps_213	1.8000E-1
ps_214	8.0000E-2
ps_215	8.0000E-2
ps_216	5.0000E-1
ps_224	3.0000E-1
ps_227	1.5000E-1
ps_229	1.8000E-1
ps_232	2.1500E-1
ps_234	1.8000E-1
ps_236	1.0000E-1
ps_373	4.5000E-1

Table 1 - Thicknesses (inches) value for 16 shell elements in baseline configuration

In the first phase, only the mass minimization was taken into account (Von Mises stress was handled as a constraint) so that a single-objective optimization strategy could be built. At this stage, the optimization process was also speeded up by exploiting Response Surface Models (RSM). Response Surfaces, or Metamodels, are mathematical models that are trained using a database of initial designs and thereafter used to predict the performance of new designs at unevaluated design points. Such approaches make certain assumption (regularity, physical meaning, statistical variability) of the response function to be modeled. In the current activity, RSMs were substituted for the Global FEM to significantly reduce the time of a single analysis.

In the second phase of the study, the optimization strategy was switched from mono- to a multi-objective for the purpose of identifying the so-called "Pareto Frontier" between mass and Von Mises stress, i.e. the best trade-off solutions.

Once each numerical analyses was performed (each such configuration generated by modeFRONTIER being referred to as a "design"), they were evaluated by means of suitable instruments for post-processing. This was a crucial point of the methodology since a smart and reliable data elaboration is highly beneficial, or possibly mandatory, given the multivariate nature of the design characterization. The first goal was to understand how the investigated system performed and later to select the best configurations. Taking into account the manufacturing requirements, the last point was very demanding: in the current case. Each thickness lay within a range [0.05'- 0.5'] was allowed to adopt 91 distinct values giving a total number of configurations equal to 91^{16} different solutions. The post-processing phase will be described below as part of the description of the data.

Mono & Multi-Objective Optimization

In respect of the mass minimization and Von Mises stress constrained to be lower than 64000 ksi, the single-objective optimization strategy exploited two different algorithms: Simplex and MOGA-II. The first one is an algorithm for non-linear optimization problems and does not require

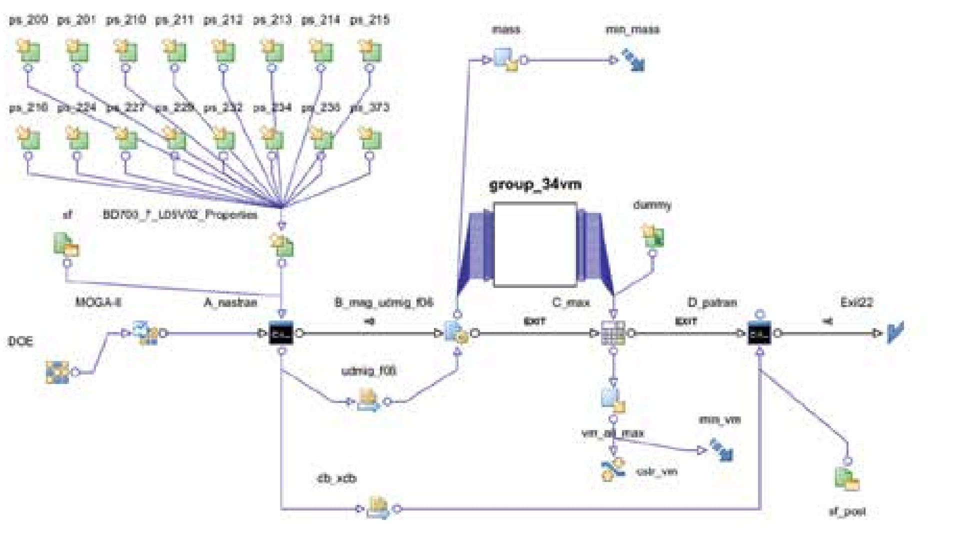


Figure 3 - modeFRONTIER workflow

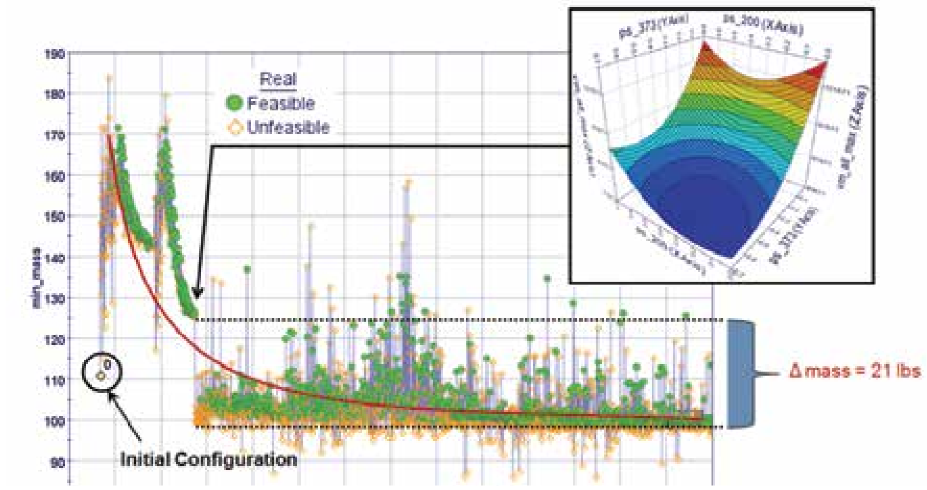


Figure 4 - History Chart – mass minimization

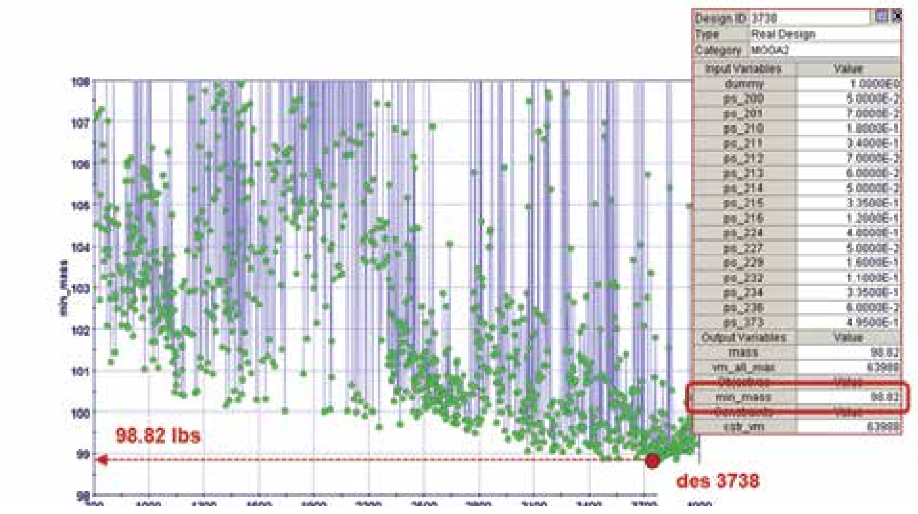


Figure 5 - History Chart for MOGA II optimization phase – mass minimization

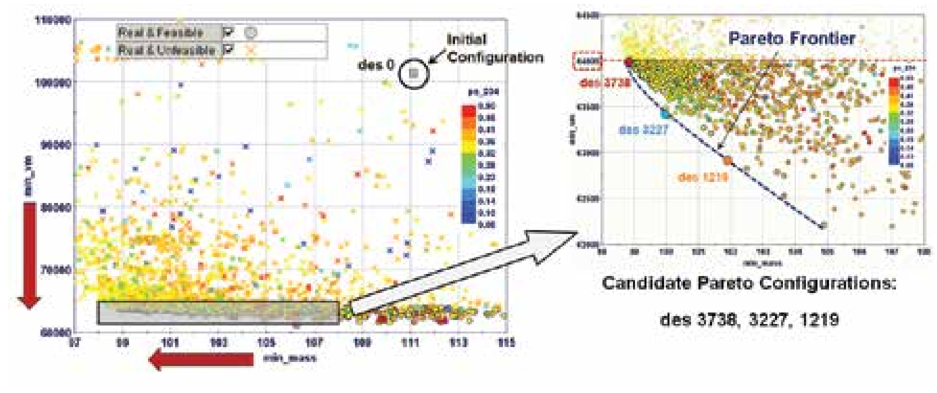


Figure 6 - Bubble Chart for multi-optimization – max of Von Mises stress vs. mass and Pareto Frontier

derivative evaluations, so it is more robust than algorithms based on local gradients. A simplex is a polyhedron containing N+1 points in a N dimensional space (thus in current activity having 16 input variables it describe a 17 point polyhedron). The Simplex is initialized by N+1 initial corners that are given by the first N+1 configurations available in the DOE table. Therefore a set of 17 initial designs were generated according to a random arrangement. The baseline configuration was introduced as design 0 for comparison. As described by the History Chart depicted in Figure 4 (in which the mass minimization is monitored versus number of numerical analysis "Design ID"), after an initial phase of exploration of the design space where most of the configurations were "unfeasible" (exceeding the constraint on Von Mises stress, and labeled with yellow diamonds), optimization evolved towards "feasible" solutions, with the mass gradually decreasing. During this phase of the study the Simplex mono-objective optimization algorithm was run twice.

With the purpose of increasing the efficiency of the optimization process, following the conclusion of design ID 700, the use of Response Surface models (RSM) was introduced: the results of the initial numerical analyses were exploited to generate the metamodels for the prediction of mass and Von Mises stress values. Amongst the RSM algorithms available in modeFRONTIER, the Radial Basis Functions (RBFs) were selected since they offer a powerful tool able to interpolate scattered data and therefore do not need training points on a regular grid - in fact RBFs are defined to be a meshless method. In addition, RBFs belong to the group of the interpolant response surface, in the sense that they pass exactly trough the starting dataset points. Generation and validation of RSMs is extremely "friendly" in modeFRONTIER environment since a powerful wizard is available.

The best virtual solutions provided by the response surfaces (virtual being related to RSMs) were then used as a new starting DOE for the subsequent optimization. At this stage the MOGA-II algorithm was employed. MOGA-II is an efficient Multi-Objective Genetic Algorithm that uses a smart multi-search elitism. This elitism operator is able to preserve some excellent solutions without bringing premature convergence to local-optimal frontiers. It is not only very robust, but since it elaborates the new designs starting from a more crowded initial population, a larger number of virtual configurations can be introduced into the new DOE table so that a more accurate exploration of design space can be guaranteed. This approach permitted the rapid discovery of a set of feasible configurations with a sudden mass reduction of about 20lbs, as highlighted in Figure 4. The best solution discovered was Design_3738 with 98.82lb mass, as depicted in Figure 5. This solution was clearly feasible, with a maximum of Von Mises stress equal to 63988 ksi. Subsequently, further studies were carried out with the aim of assessing the design solutions that represent the best compromise between the mass and stress objective functions (Pareto Frontier). In particular, instead of a constraint, the minimization of the maximum Von Mises stress was introduced, retaining the use of the MOGA-II algorithm. In this way it was possible to identify the whole set of the best

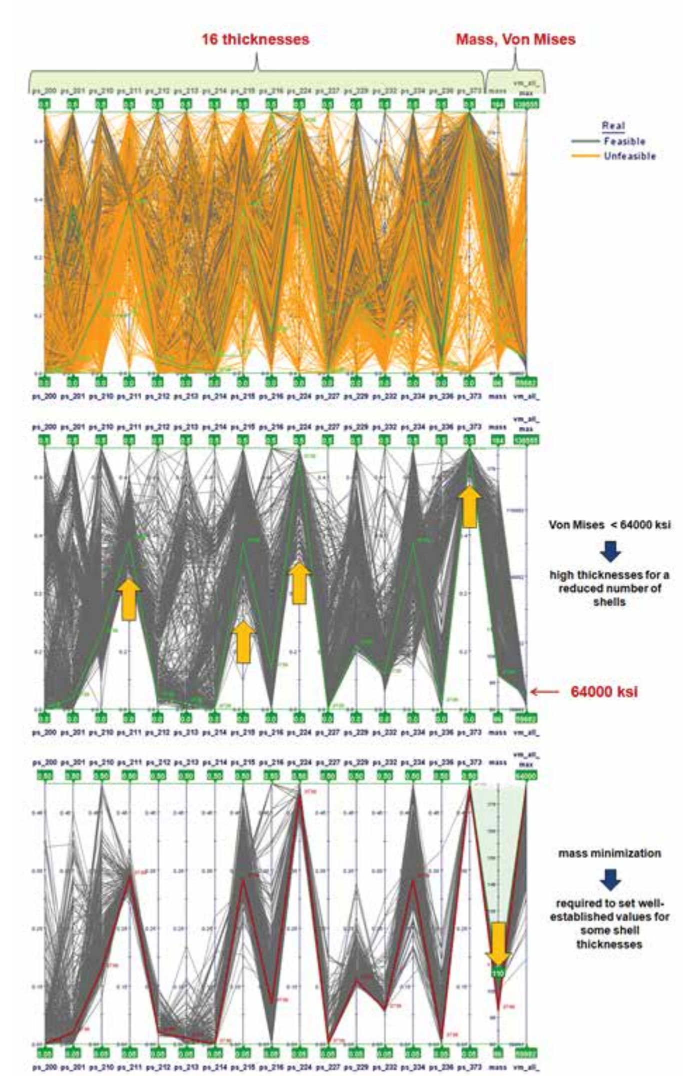


Figure 7 - Parallel Coordinates Chart

cautionary solutions with respect to the Von Mises threshold. The bubble chart provided in Figure 7 points out the maximum Von Mises stress vs. mass. It can be noted that initial configuration is located far away from the feasible region. Within the Pareto designs 3 candidate configurations (des 3738, 3227, 1219) were chosen.

Getting to Know the Phenomena

By using modeFRONTIER utilities, several detailed data analyses were performed to better understand how the investigated system works in terms of structural behavior. A very flexible and intuitive instrument (the so-called Parallel Coordinates Chart) was used. In this type of graph, firstly a set of parallel axes is drawn with the aim to represent each variable, either input or output. Each design is then represented by a single line intersecting each variable axis at the value held by that variable for that design. Since the Parallel Coordinates Chart permits the modification in real time of the range of every single variable, it can be used to filter the most interesting solutions in the database and to discover, as in this case, which designs "survive" once unfeasible designs are removed. As pointed out in Figure 7, as soon as the unfeasible designs were switched off (yellow ones disappear) the Parallel Coordinates chart makes clear that some well identified shell elements have to be set with a high thickness value to avoiding the constraint violation, whilst other ones are neglectable. In the third filtering, the minimization of mass is pursued and a set of well-established values for some shell thicknesses appeared. Comparison between the baseline and best (design 3738) windshield GFEM, Figure 8, permitted the estimation of the different thickness distributions within the numerical model and consequently the different structural behaviors in terms of stress field, deformations, etc.
As shown, smart post-processing tools (e.g. Parallel Coordinates Chart, Bubble Charts, …) grant an easy and very intuitive way to discover how the system works, matching a key requirement of methodology.
Eventually, in Table 2 a short quantitative performances comparison is sketched between the baseline configuration (des 0) and the optimum one (des 3738).

Conclusions

The exploitation of modeFRONTIER allowed the analyst to evaluate several variables in automatic way with an informative and easy-to-implement approach. The multi-objective optimization provided a high number of feasible solutions that were evaluated by the analyst in order to achieve the best configuration taking into account also other important parameters (fatigue, interface, manufacturing, etc.). Further, the multi-objective approach permitted the analyst to discover if a candidate solution belonged to Pareto Frontier (i.e. the best trade-off set), how much the baseline configuration differed from the best ones, and why different solutions worked in different manners. The modeFRONTIER workflow, enabling a complete automation of the whole analysis, allowed the maximum utilization of hardware and software resources (no CPU time wasted), and achieved a real cost saving.

Danilo Malacaria - DEMA SpA
Vito Primavera - EnginSoft

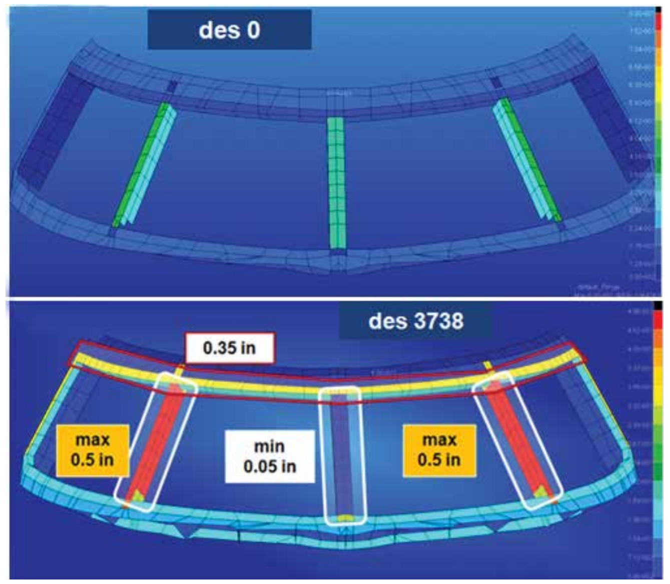


Figure 8 - FEM thicknesses – Comparison between baseline and optimum configurations

Targets	des 0	des 3738	Δ (%)
Mass (lbs)	111.13	98.82	-11%
Von_Mises Stress (ksi)	101295* Unfeasible	63988	-37%

Table 2 - Baseline Configuration (des 0) vs. Optimum Solution (des 3738)

A CAE based procedure to predict the low velocity impact response of a composite CAI specimen

The residual strength, in particular the compression strength after damage due to low velocity impact, is one of the most critical issue for composite laminates. Indeed, composite structures submitted to low energy impacts reveal a brittle behavior and can undergo significant damage in terms of matrix cracks, fiber breakages and delaminations. Such damage is particularly dangerous because it may be undetectable by visual inspection and can drastically reduce the pristine mechanical characteristics of the structure. Generally the behavior of composite materials with respect to this issue is experimentally evaluated by the standard CAI (Compression After Impact) test. For this reason, in order to simulate the impact event, an LS-DYNA FE model of this test was developed and coupled with modeFRONTIER. The integrated procedure allowed to obtain a better understanding of the influence of some numerical parameters on the simulation results (sensitivity analysis), moreover the configuration which provided the best agreement with the experimental data (optimization analysis) was computed.

CIRA

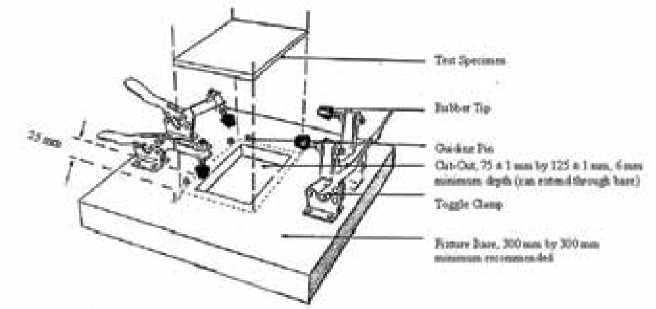


Figure 1- Impact support fixture

Test Case Description

Experimental impact tests were carried out according to the ASTM D7136 regulations to assess the capability of the procedure for investigating the impact event. A rectangular plate (150 mm x 100 mm) was impacted at an energy level of 50 J by a hemispherical steel impactor with a diameter of 20.0 mm and a mass of 8.64 kg. The material of the plate was a laminate composite with a symmetric lay-up of 28 plies [45/-45/45/-45/0/0/90/0/0/45/-45/0/90/0]s. The plies were stacked and cured in an autoclave and the resulting average cured plate thickness was 5.012mm. The specimen was held on a rigid fixture with a cut-out by means of four rubber clamps.
The impact support fixture is shown in Fig.1. The contact force, the impactor velocity and displacement were recorded during the tests. Ultrasonic c-scans were performed after each test to measure the damaged area.

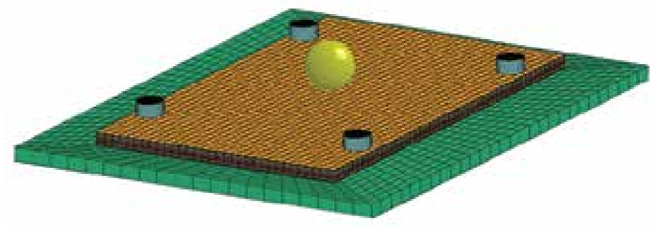


Figure 2- FE model

LS-DYNA FE model

As the plates' length and width dimensions were large compared to their thickness, a 2D modelling approach was chosen. In particular, layered shell elements with an element length of 3mm were used.
LS-DYNA's linear-elastic composite shell material model (MAT54)

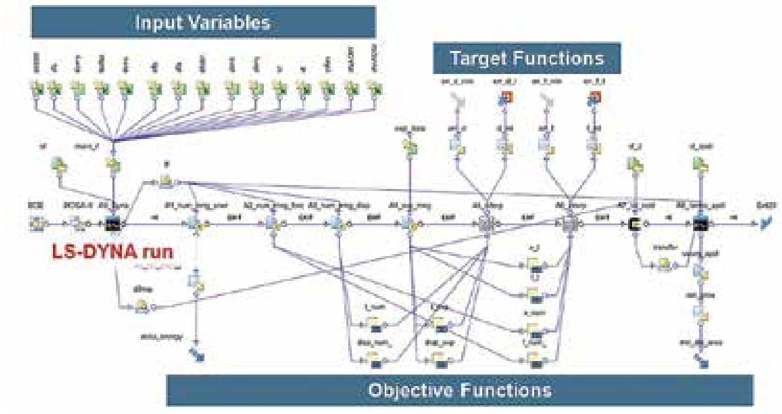


Figure 3- Sketch of the modeFRONTIER – LS-DYNA workflow

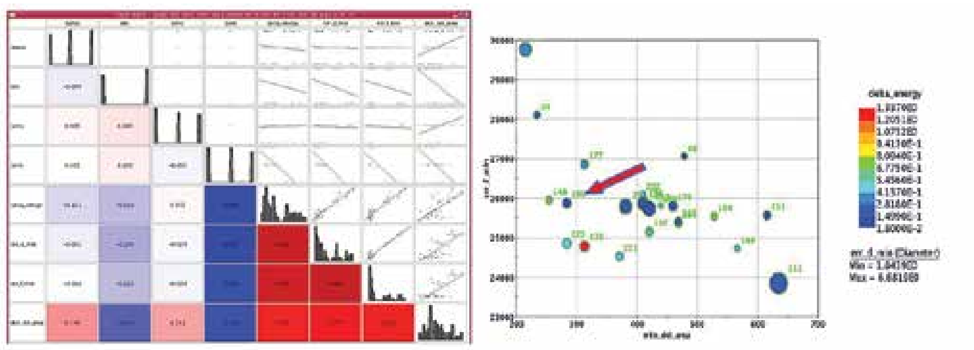


Figure 4 - a) Scatter matrix chart; b) 4D Bubble Chart

was adopted, based on the failure criteria by Chang FK and Chang KY. The separation of adjacent plies due to normal or shear loads, referred to as delamination, absorbs impact energy and decreases the laminate stiffness and therefore needs to be covered by the model as well. Because delamination cannot be represented inside the continuum shell elements, the laminate was divided into a certain number of overlayed sub-laminates connected by tiebreak contacts which were allowed to separate during the simulation according to a specified failure law. The influence of varying the number of layers of shell elements with these interleaved tie-break delamination contacts was investigated, using models with 2, 3, 7, 17, and 28 layers. A model with just 1 layer of shell elements without delamination was also investigated.

The most realistic description of the phenomenon was provided by a model with 17 layers: in this model, adjacent plies with a difference in orientation lower than 90° were grouped into a unique layer of shell elements. This was chosen for further investigations.

The impactor was modelled as a spherical rigid body with conventional shell elements and the material model MAT_RIGID. An initial velocity of 3.36 m/s was imposed on the impactor using the PART_INERTIA card. A very fine mesh was adopted in order to correctly compute the contact force between the impactor and the plate. The FE mesh used in the model is shown in Figure 2. Finally, an automatic surface-to-surface contact with the option SOFT=0 was defined between the composite plate and the rigid impactor.

modeFRONTIER – LS-DYNA process integration

In order to better understand the influence of such parameters on the simulation results, a sensitivity analysis was performed by coupling the LS-DYNA FE model with modeFRONTIER, a process integration and design optimization tool. modeFRONTIER is able to explore the design space (i.e. the permitted values of free parameters) and find configurations which satisfy several objective functions. The integration of the LS-DYNA FE model described above into the modeFRONTIER environment is roughly described by the workflow in Figure 3. The blocks on the top define the input variables for which a suitable range of variations was set. These input variables included: the damping constant (variable sf in the DAMPING_PART_MASS card), the shear strength for tiebreak contact (variable sfls in the tiebreak CONTACT card), the degradation factor for tensile failures (variable slimt in the MAT54 card) and the degradation factor for compression failure (variable slimc in the MAT54 card). Each time a new combination of their values was proposed by modeFRONTIER, the LS-DYNA input file was updated and a new LS-DYNA analysis performed in batch mode. The output of each simulation was then post-processed and the results of the analysis evaluated. The outputs used in this study were the contact force time history, the plate deflection time history, the absorbed energy and the damaged area size. Three of these output were evaluated directly in LS-DYNA (contact force, plate deflection, absorbed energy), while the damaged area was evaluated using ANSYS FE by means of an APDL macro. These numerical results were compared to experimental data during the post-processing phase and the relative errors were computed. Such errors, which will be indicated respectively as "err_f_min", "err_d_min", "delta_energy" and "min_del_area" were thus the objective functions to be minimized. In the block labelled "DOE" (which stands for "Design of Experiments") the user can generate an initial population of designs, each possessing a different combination of input variables. Starting with the results obtained from these initial designs, the "Scheduler" block iteratively generates completely new designs with the aim of achieving the defined goals using various optimization algorithms.

In order to study the interaction between the input variables and the four chosen objectives a statistical analysis was performed by evaluating an initial population of 81 designs generated by using the Full-Factorial method with 3 levels for each variables. The scatter matrix chart, which is a very useful tool to analyze the data of a statistical analysis, is shown in Figure 4a).

It was found that the variable slimt is the more significant input variable (high correlation with the 4 objectives). All parameters were found to affect significantly the damaged area objective. All objectives are positively correlated, indicating that the objectives were not conflicting. A multi-objective optimization analysis with the algorithm MOGA-II was then performed. The optimization strategy evaluated 137 designs (the initial 49 Full Factorial designs followed by 88 designs specified by the MOGA-II algorithm), leading to several candidate optimal solutions. These can be easily detected in the 4D bubble chart of Figure 4b, where each solution is represented by a coloured bubble of a particular size. A good configuration which minimizes all four objectives should therefore be blue, have a small diameter and lie towards the bottom left of the chart. Design 189 (indicated by the red arrow) was considered to be a good compromise in achieving these goals.

The correlation between the numerical results obtained with this configuration and the experimental data, in terms of damaged area size, contact force, deflection, absorbed energy time histories and force versus displacement trend, are shown in Figures 5, 6a, 6b, 6c and 6d, respectively. The comparison shows that the fitted simulation results and experimental data to be well-correlated.

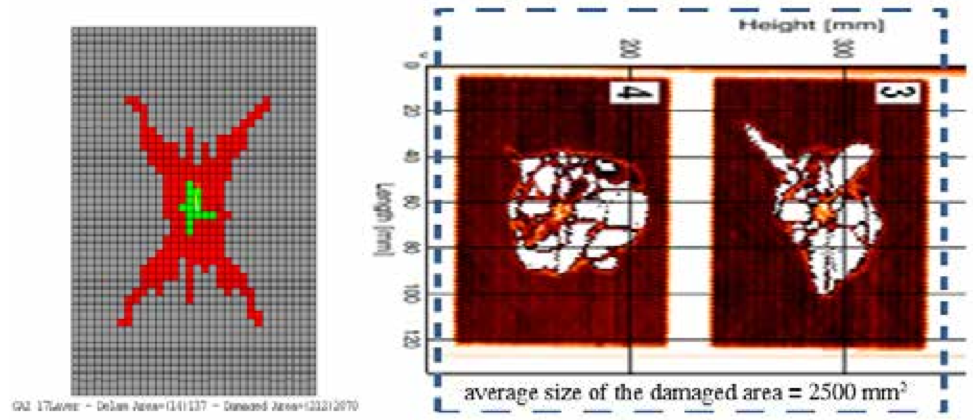


Figure 5 - Correlation between the numerical and experimental results in terms of damaged area size

Conclusion

An LS-DYNA – modeFRONTIER coupled procedure was proposed to simulate low velocity impact on composite plate. The procedure allowed the study of the influence of some numerical parameters on the simulation results and identified a configuration which provided the best correlation between the numerical results and the experimental ones in terms of contact force, deflection, absorbed energy time history and damaged area envelope.

The procedure took advantage of modeFRONTIER's automation capabilities, allowing the calculations to run automatically and unattended for 24 hours each day until completed. Once validated on an experimental database, the procedure will permit the study of a range of factors (material properties, boundary conditions, stacking sequence etc.) on the impact resistance of a component. Hence, damage resistant structures can be designed by reducing the number of expensive experimental tests.

The Aerospace Company: CIRA

CIRA was created in 1984 to manage PRORA, the Italian Aerospace Research Program, and uphold Italy's leadership in Aeronautics and Space. CIRA is a company with public and private sector shareholders. The participation of research bodies, local government and aeronautics and space industries sharing a common goal has led to the creation of unique test facilities, unmatched anywhere in the world, and of air and space flying labs. The CIRA is located in a 180-hectar area in the immediate vicinity of Capua, in the province of Caserta, north of Naples. Its has a staff of 320 people, most of which are engaged in research activity within domestic and international programs.

Rosario Borrelli, Stefania Franchitti, Francesco Di Caprio, Umberto Mercurio - Italian Aerospace Research Centre
Vito Primavera, Marco Perillo - EnginSoft

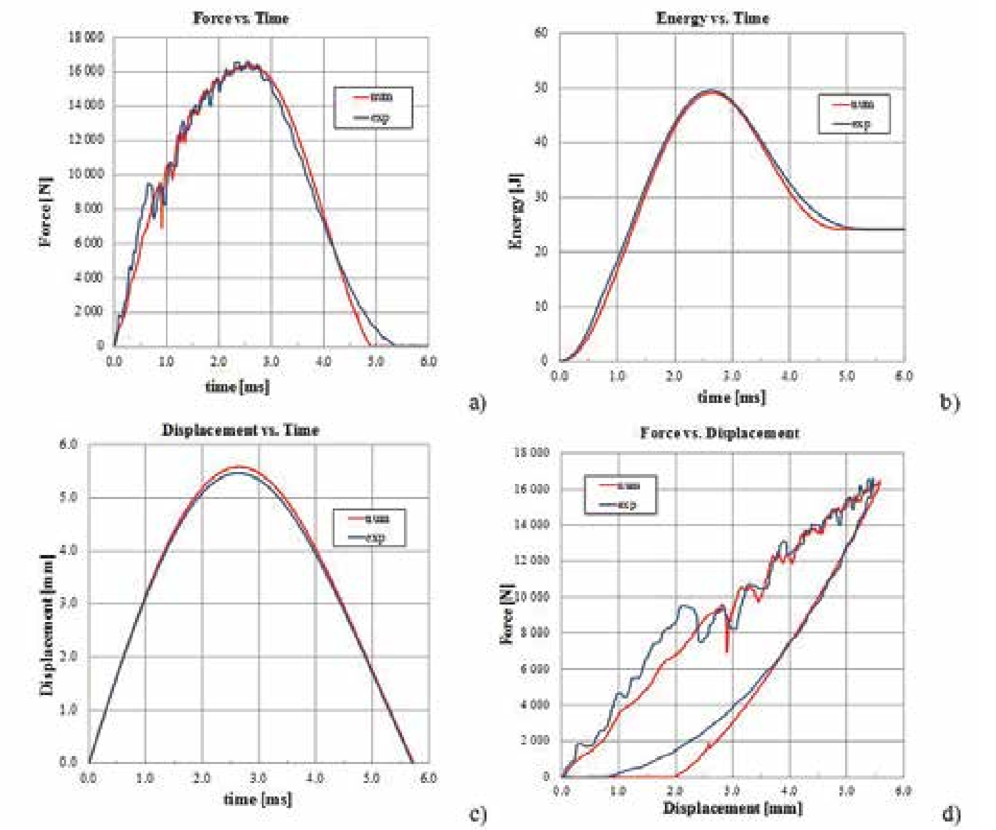


Figure 7 - Correlation between the numerical and experimental results in terms of a) contact force time histories; b) absorbed energy time histories; c) deflection time histories; d) force versus displacement trend

Multi-Objective Optimization of XBA Sentinel Antenna

A multi-objective optimization approach has been applied to the synthesis problem of the geometrical structure of antenna with complex set of requirement specification. This methodology is a promising tool for new development and application for several kind of microwave structure

A typical optimization problem regarding spacecraft antennas has been considered to improve the communication capabilities of an antenna used for down link data-handling (PDHT). These antennas play an important role in many mission of Earth Observation from Space, where high transmission rate is necessary to acquire Earth images in various spectral bands for an enormous number of civilian and military applications. The ThalesAleniaSpace first exemplary of a PDHT antenna was developed for RADARSAT and COSMO-SKY Med missions about ten years ago. For recent satellite missions new and more stringent performances are requested for the antenna pattern, especially in terms of crosspolarization discrimination (XPD) and operative frequency bandwidth.

Multi-objective optimization has been considered, combining the use of the one of the most applied electromagnetic code Microwave Studio by CST with the modeFRONTIER code by ESTECO. A first result of this approach shows modeFRONTIER capabilities to individuate alternative solution to that obtained by simple analytical formulation. Starting from this result it has been individuated a solution that meets XPD performance near to Pareto frontier. The optimization activities on the isoflux antenna constitute a promising synthesis methodology for antenna shaped pattern with wide angle coverage, when a large number of geometrical parameters are involved. The final design has been selected for a new class of antennas to be employed in future satellite constellation.

ThalesAlenia Space
A Thales / Finmeccanica Company

Problem formulation

The Power Data Handling and Transmission (PDHT) antennas are basic payloads on low earth orbit (LEO) satellites. They are characterized by an antenna pattern shaped to compensate different gain attenuation relevant to satellite slant with respect to ground station (isoflux pattern). The challenging problem of the antenna design is the structure optimiszation to meet more requirements as

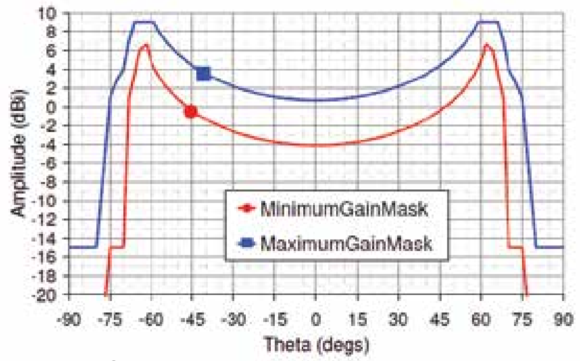


Figure 1 - Antenna Gain Requirement Mash


Figure 2 - Engineering Model of PDHT Isoflux Antenna with Several Series of Slots along Radial Direction

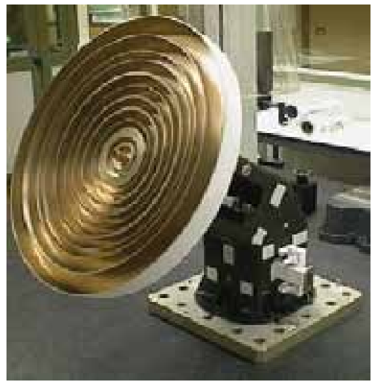


Figure 3 - Previous Flight Model of PDHT Isoflux Antenna, Corrugated Structure fed by dielectric Loaded Launcher

the gain definition on desired mask defined on extended coverage area (up to 64 degs in elevation and complete azimuth range), crosspolarisation discrimination, amplitude and phase ripples in band, return loss (Figure 1).
The basic antenna architecture is a symmetric cylindrical corrugated surface fed by quartz loaded open waveguide launcher (Figure 2), so that the analysis is based on simple 2D Method of Moment modelling, while the optimization is performed by a quasi-Newton minimization techniques. More stringent antenna requirements entail a redesign of the electromagnetic/geometrical structure: to improve the electrical performance a series of slots across the corrugation walls have been inserted (Figure 3) The break on the geometrical symmetry requires now more complex 3D e.m. description with large increasing on computation time and memory resources. The global geometry definition should require over 100 independent variables, so that the possibility to optimize the antenna performance becomes very strong demanding, taking into account 6 hours for a single computation run (4 CPUs Xenon at 3.0 GHz).

The multi-objective/multivariable nature of the optimization problem derives from multiple requirements on electrical antenna performances, with appropriate weight if necessary. These mutually dependent RF parameters derive from operative parameters as satellite and antenna position, visibility angle, pointing error angle, minimum gain at Nadir, etc:

Gain requirement defined with respect a mask in a well defined angular range and in a particular frequency bandwidth;

- Gain ripple requirement with respect the frequency;
- Phase Ripple requirement (quadratic component of the gain) with respect the frequency;
- XPD requirement defined, in the same manner as the gain, in specified angular and frequency ranges;
- Return Loss requirement;
- Mechanical feasibility of the theoretical geometrical structure

yields very difficult to explore the complex solution space in order to obtain the best geometrical structure. Because no analytical models are available for this complex structure the only possible way to solve the problem is the numerical approach. The most important topics in the optimisation problems are:

- the definition of the searching space and the wellposed definition of the objective function;
- The identification of solutions that goes toward the convergence of the objective functions.
- “minimal approach” with a geometrical structure profiled by an established function (polynomial function, trigonometric function) in general described by few variables;
- “aimed approach” that divides the variables in homogeneous classes and acts only on one group per time, appropriately individuated.

Taking into account the particular nature of the electromagnetic problem the range for the variation of geometrical dimensions has been established into a half wavelength. The starting point for the optimization has been chosen taking into account the experience matured on the previous PDHT design activities configuration.
The powerful capabilities of the modeFRONTIER optimization

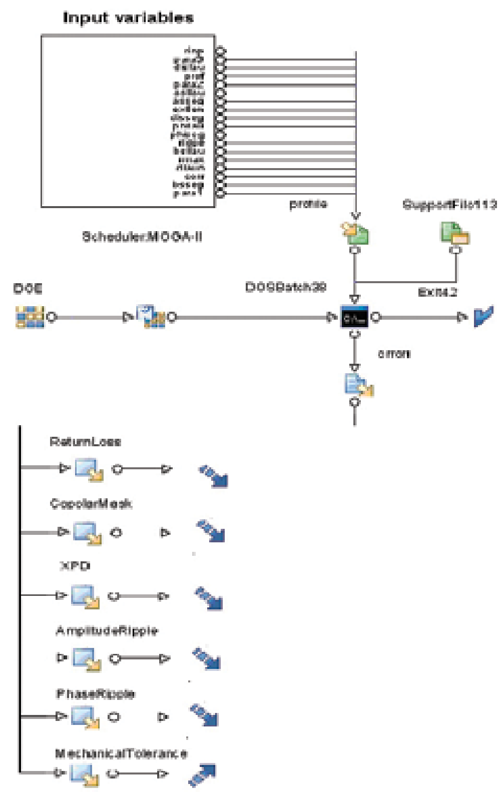


Figure 4 - Structure of the Optimization Flow: modeFrontier WorkFlow

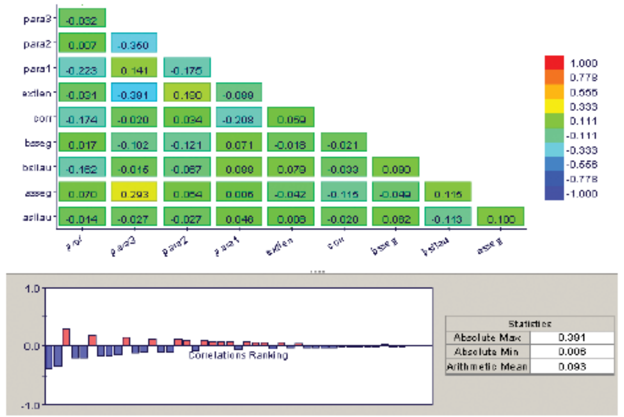


Figure 5 - Correlation Chart for main set of Variable

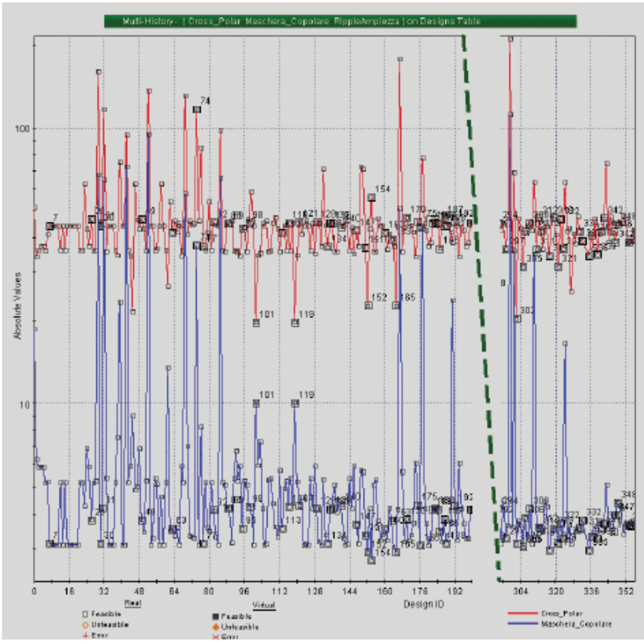


Figure 6 - Multi-history char (Cross-polar Vs Co-polar Mask)

ambient, the Microwave Studio CST tool for EM analysis and dedicated interface software have been used to individuate the optimal solutions.

Description of optimization flow

modeFRONTIER philosophy has been chosen to search a good solution of the electromagnetic problem. A family of experiments has been generated and a series of electromagnetic analysis have been performed to compute the relative class performances.

Figure 4 describes how the control flow works. The global optimization process has its core on the modeFRONTIER interaction with other software. The modeFRONTIER software takes in input the geometrical parameters to describe the structure with the indication of the set of the variables to change and the values of the desired objectives. A software developed by Thales Alenia Space is devoted builds the geometrical structure (model file) giving it in input to Microwave Studio CST electromagnetic software and it post-processes the Microwave Studio CST results in order to compute the relevant error functions.

Optimization

The individuation of the more sensitive variables has been an important step in the optimization starting phase. A DOE (Design of Experiment) technique has been used to understand better the input-output relationship and to reduce the design space dimension (number of variables) combining Sobol and Latin Square methodologies. A correlation scheme among the optimization variables is reported in Figure 5.

The correlation map of the variables considered in the optimization gives information on the dependence among the parameters (Figure 8). For example the parameters para1, para2 and para3 have the effect to modify the surface profile, while extlen sets the position of the launcher with respect to surface. The high correlation coefficient of extlen with para2 and para3 gives the evidence of the similar physical effect that these variables have on the output variables considered.

In Figure 6 the history chart is reported for the main electrical parameters (copular mask and XPD). The result shows that id 152 is the better compromise for these two goals. The same result is reported in the bubble chart with more evidence of zone near the Pareto frontier (Figure 7).

Results

More performing solutions with respect to requirements have been individuated by the optimization process. Among the more challenging solutions the selected one has a high degree of regularity in terms of corrugation depth, corrugation steps, dimension of the coupling slot. These results have been reached by the powerful modeFrontier capability to individuate the sensibility between the geometrical data and performance (or in other words the different objective functions).

With regard to desired performance modeFRONTIER has been able to obtain the following improvement with respect to old configuration, in particular:

- The gain mask has been fully satisfied, with desired improvement of the gain at 62° (6.6 dB now w.r.t. 6 dB) (see Fig. 8);
- The pattern widening on the enlarged coverage has been achieved so that the antenna can be used for the lower satellite position with 70 degs field of view;
- The XPD increase of 7 dB passing from 5 dB to 12 dB;
- The amplitude ripple in carrier band has been satisfied with 1 dB (peak to peak) variation. The new solution presents a equalized copular pattern over a large frequency bandwidth;
- The phase ripple in carrier band is satisfied with 3 deg (peak to peak) variation.

It is evident a good improvement of XPD in the central coverage region comprise between ±50 degs. In the final antenna structure the cross-polar peak has been reduced to - 15dBi in comparison to -5 dBi with plus 10 dB decreasing. Another very interesting improvement on the antenna diameter is could be possible: it has experienced during the optimization process that a reduction of the diameter is reachable. Antenna geometry with a 300 mm diameter could be able to maintain the same performance (with the only drawback to have a minor pattern slope out of the coverage).

The reduction of the size has been showed as a new solution with good advantages on the antenna satellite allocation.

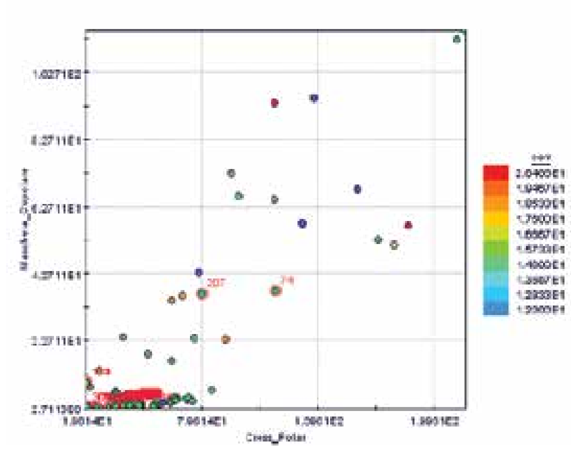


Figure 7 - Bubble Chart relevant to XPD and Co-polar Mask)

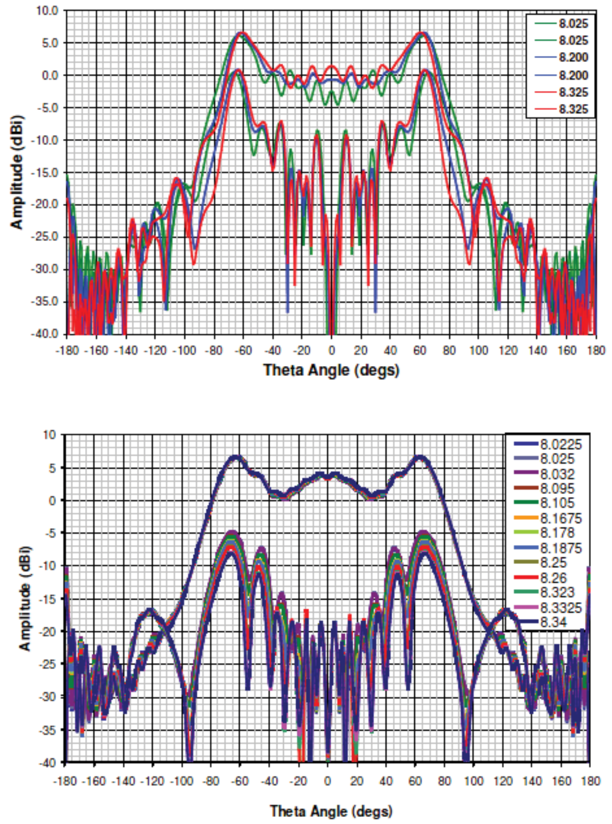


Figure 8 - Results of Optimization: a) Previous Configuration – b) After Optimization

Conclusions

The potential of the combined use of modeFRONTIER with electromagnetic tools (as Microwave Studio by CST) has been demonstrated for a isoflux antenna synthesis, which constitutes a very complex e.m. problem, especially when low XPD is requested on a wide-coverage. This procedure could be a first step in the development of more advanced design procedures based on the modeFRONTIER environment. In particular it has to emphasize:

- Research of the theoretical performance limits for e.m. configuration (typical research of Pareto frontier);
- Individuation of the robust design in terms of sensibility analysis, envelope minimization and weigh (important for space application);
- Individuation of the transfer functions (using the modeFRONTIER capabilities of the Response Surface Methodology) as system response to permit the their use in other complex systems (smart antenna system, reconfigurable antenna, multibeam adaptive antenna systems)
- Material characterization and parameters extraction and technological process refinement.

Acknowledgement

The authors would like to thank Mr Peter Rinous, ESA for valuable suggestions on antenna development.

R. Ravanelli - Thales Alenia Italia Co.
C. Iannicelli - Software System Engineering Co.
F. Franchini - EnginSoft

Fueling optimal propulsion for a space rocket

L75 Engine – The Challenge

IAE Instituto de Aeronáutica e Espaço

The objective of Project L75 is to design and develop a liquid propellant, turbopump-fed rocket engine capable of generating 75 kN of thrust (vacuum). The main purpose of this type of engine is to be part of the upper stage of any satellite launcher vehicle, including VLS-Alfa and VLS-Beta.The project began in 2008 with the Brazilian Space Agency (AEB) sponsorship and in 2012 the German Space Agency (DLR) and Fundação de Desenvolvimento da Pesquisa (FUNDEP) partnered up in the testing phase of the L75 engine.

Despite the advantages of liquid propulsion for rocket engines, when the project kicked off, the majority of studies available concerned solid propulsion. Because liquid propulsion provides better control of the satellite launcher during the launch phase, consequently reaching a more precise satellite orbit injection, the team at IAE decided that the liquid propellant option required further investigation.
The first configuration of the L75 Engine used a propellant pair constituted by liquid oxygen and kerosene, capable of generating an estimated specific impulse of 324s and 75kN of thrust in vacuum. The specific impulse is calculated as the Thrust / (Mass Flow * Gravity), where the mass flow considers both fuel and oxidizer.
The gas generator cycle was designed using well-established methods, with the main combustion cycle taking the propellant pair and pumping it to the combustion chamber. In this system, the turbopump design is crucial since the mass of propellants is quite relevant and the gas generator requires about 400kW to drive the pumps, generated by only 5% of the rocket propellants.

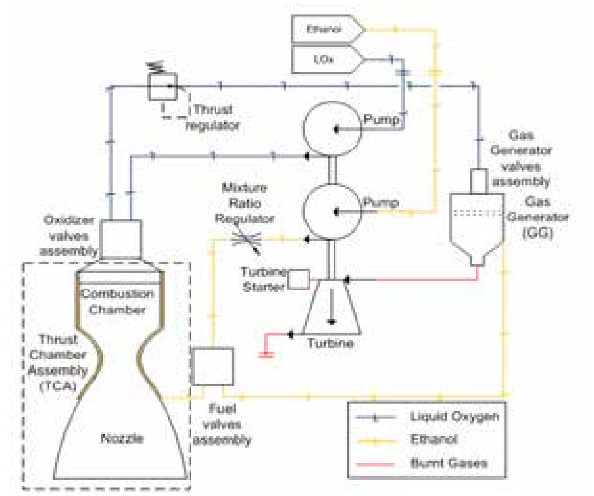


Figure 2 - L75 Engine cycle: gas generation

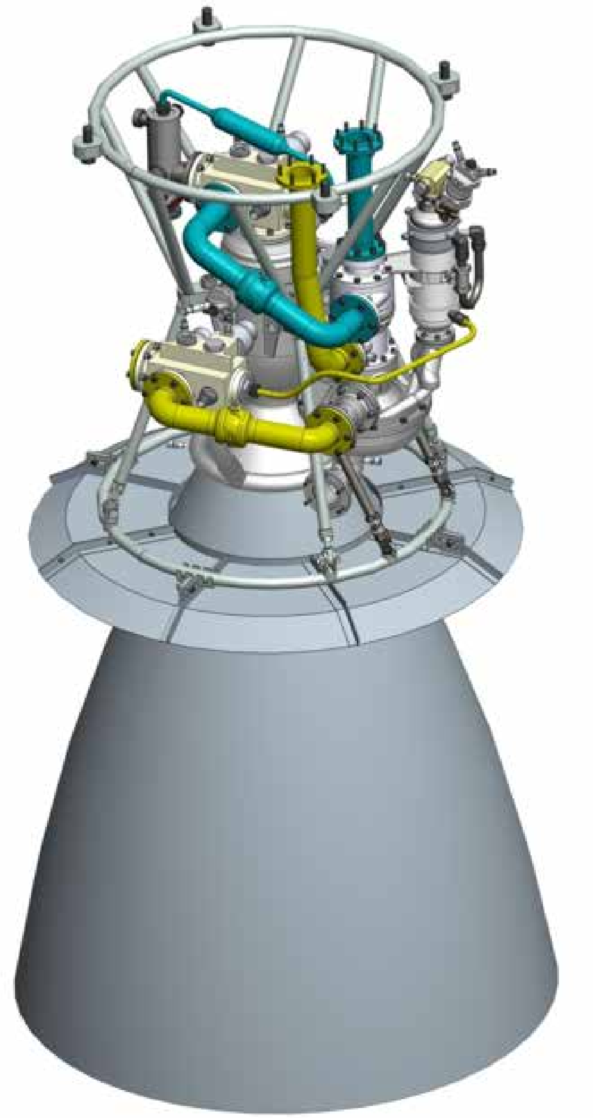


Figure 1 - L75 Engine model

Temperature handling is one of the many delicate aspects of the Thrust Chamber Assembly (TCA) design and has to be kept under control to prevent failures. The reasons why the team opted to switch to an ethanol/oxygen combination were lower investments, availability of ethanol as opposed to rocket grade kerosene (RP-1) and the foreseeable environmental restrictions regarding kerosene test stands in Germany.
With ethanol, a fraction of water can be added to the fuel mix to better handle the cooling process in the combustion chamber and improve combustion stability. A drawback of the ethanol option is reduced energy availability (30% less compared to kerosene, being ~30MJ/kg against ~45MJ/kg) hence the new challenge was to maintain the same level of thrust with the new fuel mix.

The water portion in the fuel mix, pumps and turbine efficiency targets and five thrust chamber parameters (pressure, mixture ratio, throat diameter, area expansion ratio, film cooling flow) were chosen as input variables to analyze the impact on the combustion and of final rocket performance. With ethanol and water the reaction parameters are different and engineers had to make sure that the combustion still occurs at specific conditions. A reverse calculation of the chemical equilibrium models was implemented to find the target values for the combustion.
An advanced, nested RSM-based optimization workflow was set up to predict system behavior and calibrate the fuel mixture ratio

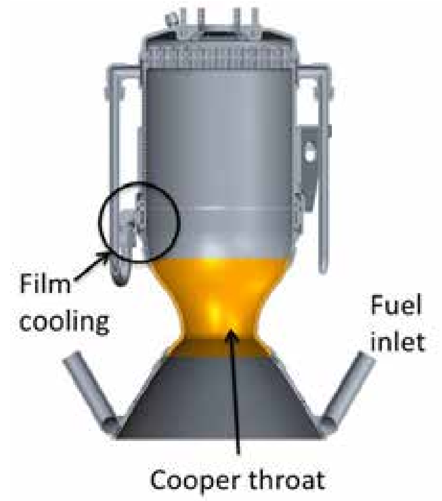


Figure 3 - Thrust Chamber Assembly (TCA) cycle design

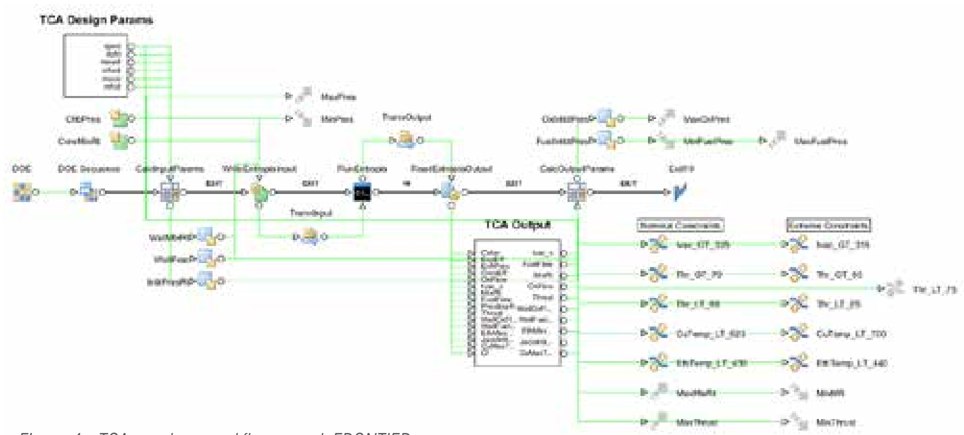


Figure 4 - TCA envelope workflow - modeFRONTIER

for the target temperature, in relation to given values of the water fraction and pressure. A DOE was calculated to generate the reverse combustion RSMs and these values were treated as inputs to create another response surface that investigated the combustion patterns. Variables were then handled by the external workflow to meet the desired temperature that returned the best fit. RSM allowed engineers to quickly evaluate the temperature response instead of using a computationally intensive nested direct optimization.

Following this initial analysis, it was then possible to create the complete engine cycle design workflow, combining the simulations for the main combustion chamber (RSMs), the TCA design (in-house tool) and gas generator combustion (RSMs).

First, the engine design was considered by investigating the following TCA variables: combustion chamber pressure, mixture ratio, throat diameter, nozzle area expansion ratio, film cooling flow, water fraction in fuel, pumps and turbine efficiencies. Constraints involving the TCA design were height, diameter, fuel pump outlet pressure and thrust. Additionally, two strategies for temperature cooling were considered: one injects fuel along the chamber wall to create an evaporating film that protects the wall from hot gases while the other employs a stratified combustion with colder gases near the chamber wall. The team opted for the second option. While many recommendations concerning the relations among engine internal parameters were taken from established Russian literature, the team decided to study the aspects regarding safety in depth. A design value of 900K was set for the turbine inlet temperature to reduce the risk of failure for the first turbopump and to keep some margin to increase the temperature and consequently obtain an increased thrust.
The statistical analysis tool in modeFRONTIER provided designers with a useful support tool to spot the main variables in relation to the Specific Impulse and disregard the ones having little impact.

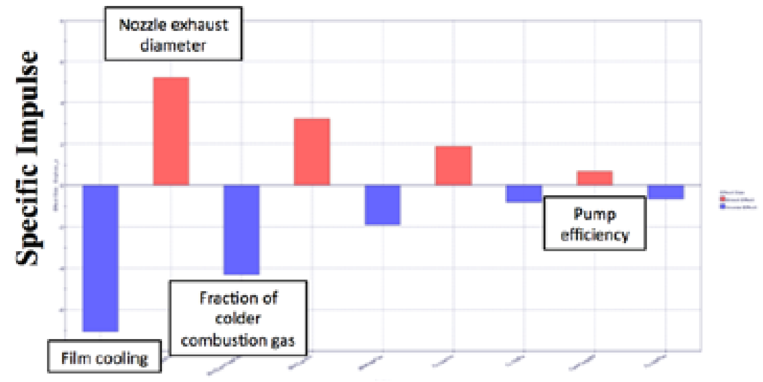


Figure 5 - Study on Specific Impulse main variables

The film cooling obtained by injecting fuel into the chamber showed a remarkable inverse influence on the impulse, producing further complexity in the design; a detailed thermal analysis led to the elimination of this film and the adoption of a colder combustion gas near the wall. The nozzle exhaust dimension was also identified as being a very important variable requiring engineers to find the biggest diameter of outlet possible. Pumps and turbine efficiencies instead did not have as much impact since the turbopump operates with only 5% of the propellants. Once the important variables were spotted, the workflow streamlined the computations and identified the best engine configuration to generate the thrust sought after. The level of insight gained by exploiting the design space exploration and statistical analysis phase allowed the design point choice to be made simply by navigating through the Neural Networks RSM charts, saving a significant amount of time.
Additionally, despite using the less efficient fuel option the identified design allowed for a mass flow similar to the kerosene , which means the same performance metrics, enabling a better TCA cooling (30% increase in fuel flow), safer turbine (16% reduction of turbine inlet temperature) and pressure expansion ratio which improved by 60%.

The solution was simplified thanks to the reduced temperature and pressure: turbopump rotation speed was reduced, thereby improving the operation conditions and the gas pressure expansion ratio was enhanced by using all the available space.
Once the best design point for the engine parameters was obtained, the second study analyzed the thrust chamber to define the physical

Parameter	Kerosene version	Ethanol version	
Thrust	75 kN	75 kN	Same specific impulse
Total mass flow	23,5 kg/s	23,5 kg/s	
Liquid oxygen flow	16,2 kg/s	14,0 kg/s	
Fuel flow	7,3 kg/s	9,5 kg/s	Better TCA cooling
Combustion chamber pressure	70 bar	60 bar	Less complexity
Turbine inlet temperature	1073 K	900 K	
Turbopump speed	30.000 rpm	24.000 rpm	
Pressure expansion ratio	1400	2248	Uses all available space to expand the gases

Table 1 - Comparison between kerosene (baseline) and ethanol (new design) engine parameters

region where its operation is safe and viable, called the operational envelope. An envelope definition is needed, for instance, to derive interface requirements, for structural dimensioning and TCA test planning.
Using modeFRONTIER, the team created a workflow where operational variables, such pressure and mixture ratio, were represented as design variables of an optimization problem. Several different objectives were defined to ensure that the whole operational space was investigated: minimum and maximum combustion pressure, mixture ratio and propellant feed pressures. The operational constraints, such as thrust, specific impulse, maximum allowed metal temperature and maximum allowed ethanol temperature (to avoid boiling) were represented as constraints for the optimization problem.
Since there are several operational constraints with two levels for each constraint - regarding nominal and extreme envelopes used for qualification and interface/structural sizing respectively - it can be very time consuming to find all the operating conditions that lie on the edges of the envelopes.

The MOGT algorithm was used to find these operating conditions by performing all combinations of maximization and minimization of operating conditions for each set of nominal and extreme constraints. Each combination was manually configured as an individual optimization run.
To speed up the search, RSMs of an in-house code were used to analyze the TCA envelope configuration. More than 15,000 evaluations were obtained, combining optimization runs, which resulted with the designs concentrated around the edges of the envelope. With the support of the post processing tools in modeFRONTIER the data were further investigated and the TCA off-design operational envelope was identified.

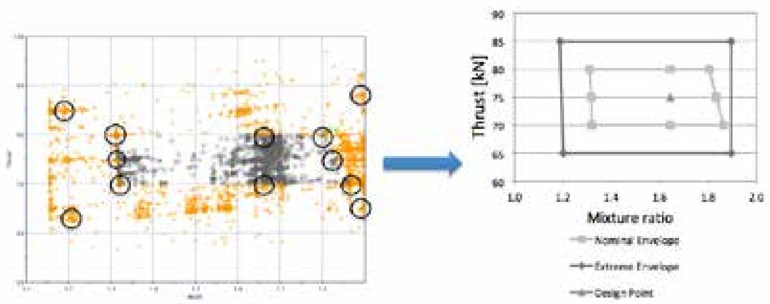


Figure 6 - TCA envelop operational space plot and optimal design

Conclusions
This work consisted in two applications of modeFRONTIER in liquid propellant rocket engine design. In the first study, modeFRONTIER is used to optimize the high-level engine parameters and geometry for a liquid oxygen/ethanol engine aiming for 75 kN of thrust. The use of DOE, surrogate-modeling and statistical analysis allowed the team to greatly simplify the design problem, resulting in an engine that can be as propellant-efficient as another kerosene fueled engine for the same thrust level, but which was designed without such techniques. The second application uses modeFRONTIER as a search tool for defining the operational envelope of the TCA, completing the design of the engine of the first application. The TCA's operational constraints are modeled as optimization constraints while parameters needed to define the operating condition are modeled as objectives. A multi-objective algorithm is then used to maximize or minimize the operating conditions accordingly. The result is, therefore, a set of operating points that lie on the edge of the TCA's operational envelope.

Bernardo Reis Dreyer de Souza
Space Propulsion Division
Institute of Aeronautics and Space – IAE

The Instituto de Aeronáutica e Espaço
The Instituto de Aeronáutica e Espaço– IAE is part of the Department of Science and Aerospace Technology of the Brazilian Air Force and since 1954 its 70 laboratories have been committed to the research and development of new solutions for the field of aerospace engineering. Major projects include the study of materials, propulsion, aerodynamics, guidance, control, meteorology, telemetry, sensors, on board software and acoustics. Project L75 aims at developing advanced expertise and technologies in the liquid propulsion field. In particular, the team studied the design for a rocket engine using liquid propellant such as liquid oxygen and kerosene or ethanol, serving the upper stage of satellite launch vehicles. Since the fuel conversion from kerosene to ethanol in 2014, engineers have worked with modeFRONTIER to find the most efficient fuel combination and cycle setup to satisfy the required thrust and fine-tune the engine parameters to respond to design constraints.

ESSS ESSS has gained an international reputation by offering a complete range of numerical simulation solutions to the market, accompanied with premier customer support and related engineering services which allow customers to fully harness numerical simulation solutions in all sorts of engineering fields. ESSS started its partnership with ESTECO back in 2006 and since then has been helping to spread the optimization platform modeFRONTIER to a wide spectrum of industries, including oil and gas, aerospace, automotive, and energy. ESSS has also expanded its operations beyond Brazil by establishing affiliate offices in Argentina, Chile, Colombia, and Peru. The company has over 150 staff members, providing support to a customer base of more than 500 South American institutions.

Figure 1- Sailing boat produced by Perini Group

Multi-objective Optimization study of the highest aluminium sailboat main mast for Perini Group

Perini sailboats have been always acknowledged high performances in terms of balance, speed, reliability and safety, paying a special attention to aesthetic details and comfort. Such distinguishing and well consolidated features are combined with constant improvement in technical solutions and in a widening range so to meet the customers' growing requirements.
Considering such context, a pilot project has been developed, taking advantage of automatic optimization techniques based on virtual prototyping. In order to carry out a really meaningful project from the company point of view, some important aspects have been taken into account, such as the choice of a sector with a considerable knowhow able to provide at the same time positive and direct productive implications, though coming from a typical R&D activity. Going into this project details, born of Perini and EnginSoft collaboration, it concerns the optimization of the mainmast structural part of a new sailboat special series.
The study aims at the identification of the best solution able to guarantee the combination of the lower weight with certain buckling factor, both globally and locally. The accurate FEM scaling implies not only a weight reduction in the mast structure but also more the 5-7 times saving in the keel one, thus increasing the sailing performance of the boat.
Further important implications are the considerable savings due to the high cost of high resistant aluminum and lead alloys used for the keel, an easier product construction thanks to a reduction in plate weight and thickness, a shorter time-to-market (reducing the time for plate welding and assembly), easier mastings, greater sail comfort, thanks to a reduction in heeling performance being equal.

Figure .2 - Picture of the mast

PERINI NAVI

The design methodology consists of the analysis of the first (global) buckling factors on the transverse and symmetry plane.
The model has been totally created in Workbench using DesignModeler and including link elements through command. The model consists of LINK10 for shrouds and stays, BEAM188 for mast panels and crosstrees, while the connection between the panels and the crosstrees through cp has been carried out via command.

The information concerning the mast section properties, for its six parts in terms of inertia and area, have been parametrically included in the model within the real constants. The section model for the six parts has been worked out and parameterized in Workbench.
The variation of the geometric parameters, which define the shape of the section, identifies a values range for the area and the inertia moments of the section. Such values are the input ones used for the above-mentioned global model. To carry out the analysis of both global and local buckling, the pre-stress effects due to the falls have been taken into account.

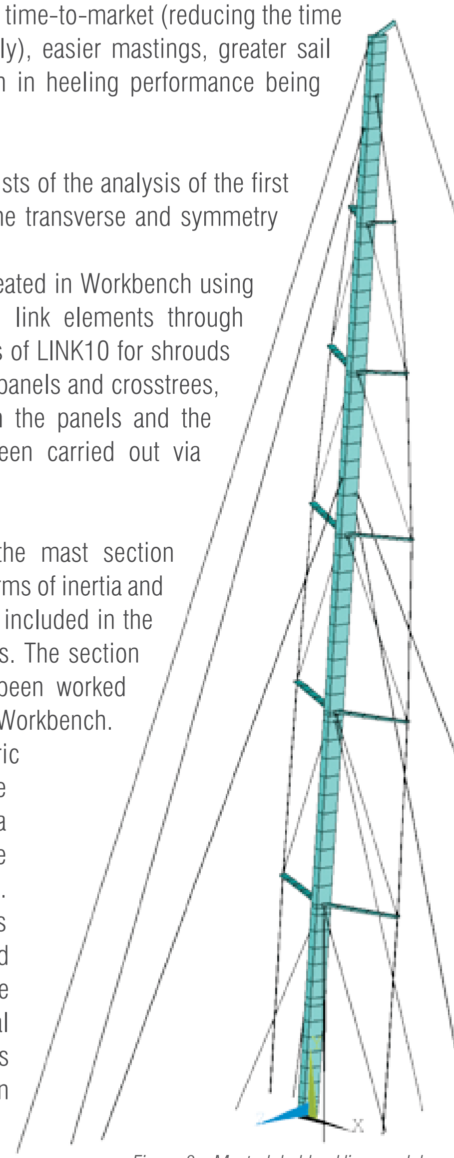


Figure 3 - Mast global buckling model

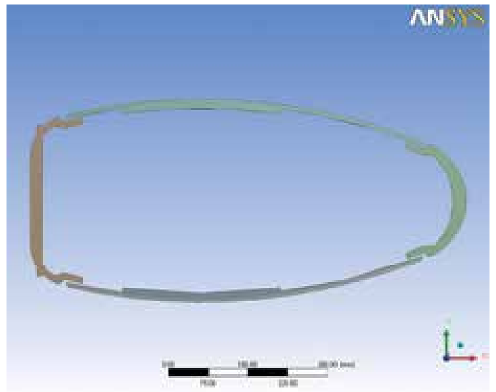


Figure 4 - Mast section worked out in Workbench

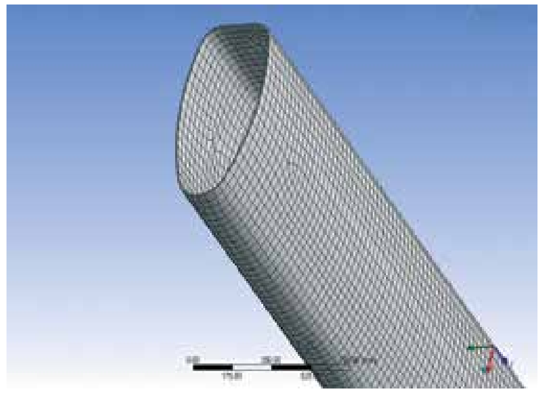


Figure 5- Mast local buckling model

On such regard, a first pre-stress static analysis has been set, followed by a linear buckling analysis. The integration procedures of the three Workbench models and the associated optimization process have been developed within the modeFRONTIER platform, a multi-disciplinary optimization software (MDO tools).
The variables, that modeFRONTIER has automatically processed in order to improve the project configurations, are the same geometric parameters the designer normally acts on, according to its experience. In fig. 6 is presented the workflow created in modeFRONTIER, where the three Workbench models (the section one, the global buckling one and the local buckling one) are referred to and jointly managed.

An integration process as such obviously has a certain impact on the previous design methodology, imposing on one hand a parametric set effort under strict requirements, but guaranteeing on the other hand, the exploitation of the whole available potential of the modeFRONTIER platform coupled with ANSYS WB/Excel/in-house code and consequently the exploitation of HW/SW resources available. On the other hand Workbench has allowed the robust regeneration of the numerical model, according to the variation of the input parameters, the automatic application of the boundary conditions, the automatic recognition of the contact areas, the possibility of carrying out advanced elaboration through pre- and post-processing commands. Thanks to modeFRONTIER versatility features, it has been possible to adjust both sensitivity analysis of input variables and extensive optimization process, in order to get the optimal results in terms of effective structure lightening and material and time saving during machining. The optimal point decreased 20% of weight and around 11% to 16 % of buckling factors.

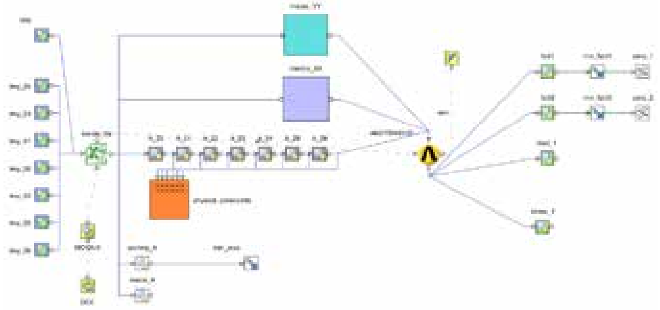


Figure 6- Analysis Workflow

Figure 9 – Sensitivity Analysis Results

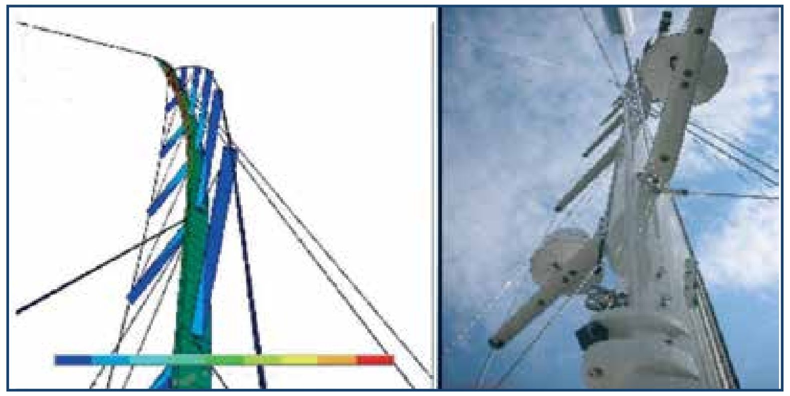


Figure 7- Preloading strain field

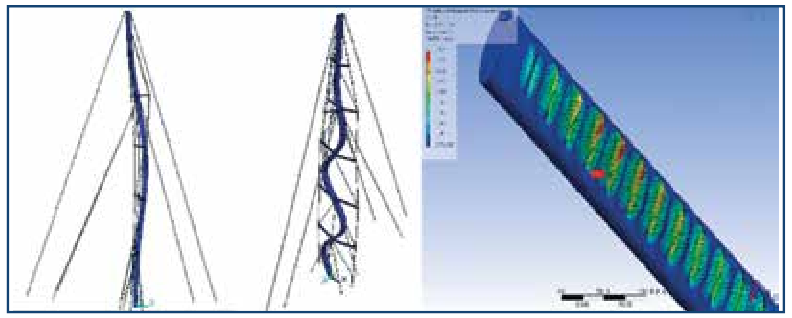


Figure 8- Shapes of global and local buckling

The advantage is really notable not only in terms of results: the created procedure can be applied to similar structures and can be easily further detailed and adjusted to different requirements for the benefit of efficiency, reliability and after all of a real product and process development.

Franchini Francesco, Valentina Peselli - EnginSoft
Matteo Paci - Perini Navi

Parametric FEM model optimization for a pyrolitic Indesit oven

2009 Ecohitech Award: Recently, Indesit Company has won the prestigious Ecohitech Award and thus earned itself an "eco-virtuous enterprise" status.

By examining only the internal glass of the pyrolitic oven which consists of visco-elastic material, the optimization process obtained the minimum stress distribution and stress gradient.
To successfully finalize the work and to deliver the best possible technical results insuring highest quality standards are met, the following analyses have been performed by Indesit and EnginSoft:

1) Parametric FEM model creation with ANSYS
2) Creation of workflow in modeFRONTIER and ANSYS integration into Frontier's loop
3) Optimization of the clamping system by an automated routine defined within modeFRONTIER
4) Results analysis and optimum design extraction according to the given objectives

The present device belongs to a new type of the Indesit domestic oven range, called Pyrolitics.
Indesit's new technology allows a fast cleaning of oven cavity, by means of a pyrolysis process that burns encrustation caused by cooking. The Pyrolysis process starts at temperatures close to 500°C which are extremely high for a traditional device considering an external temperature of 20°C. This environment produces an high thermal gradient which considerably deforms the glass.

The door structure of the oven is made of a triple-glass system, whereas each is separated by an air wall to guarantee rapid heat dissipation and to respect the safety regulations which limit the allowed external glass temperature to 60°C.
Glass stresses are derived from the thermal gradient, established between its surfaces, and produce a consequent deformation; an inappropriate glass clamping system would probably increase internal stresses and cause rupture.
From experimental tests, we have learned that the internal glass is exposed to the highest stresses; in fact, this is the component with higher thermal gradients between its faces. The aim of this work was to develop a methodology that allows to simulate the real working conditions of the glass and to find an optimal glass clamping solution that minimizes the stresses.

Figure 2.2.1 – Temperature measuring point on internal glass

2 Structure of the model
2.1 Solid model

The model provided by Indesit has been made of a 3D door model of the oven with the actual glass clamping system. The door is composed of a 3 glass system, mounted on a specific structure that keeps them parallel and separated in order to allow the passage of the air cooling flow. This model has been simplified in order to obtain a complete glass clamp system to

reproduce the real door-clamping solution.
The provided material included some elements, such as, chamfer and a non-functional fillet that have been deleted in order to create a simplified model far easier to analyze. Constraints characteristics and glass geometry have been maintained in order to produce a suitable approximated model.

2.2 Experimental measures
After some experimental measures, a series of grid-organized values of temperatures on the internal glass of the oven, was provided by the user. These glass temperatures were obtained by some thermocouple probes on the point highlighted in picture 2.2.1.

Many repeated tests were performed in order to minimize the error of measure, and an average value of each measuring point was taken into account.
In this verification, we have considered the maximum measured values to reproduce the worst working condition.

3 Glass modeling
3.1 Thermal modeling of the glass
In order to perform a FEM analysis, it was necessary to assign to each node its temperature, but we had only eight measured points, that is why, the available value was modeled by using a RSM application. In fact, we used the eight measuring points to build an opportune RSM that reproduces the glass-temperature distribution with a good approximation.
A Response Surface, also called meta-model, is a post-processing tool of modeFRONTIER; in this application an approximate RSM was chosen, because all measuring points may be affected by a measuring error, due to uncontrollable thermal effects (e.g.: radiation and convection).
In picture 3.1.1, an approximate function and relative approximation error graph are shown.
Apart from obtaining a continuous tool able to estimate temperatures of all values including a variable space definition, using modeFRONTIER allows to obtain an analytical form of this surface.This expression will be used in the FEM modeler (ANSYS) to assign temp value on each node.
The next step is the application of the analytical expression to the FEM model. In picture 3.1.2 we observe the glass with the applied temperature.

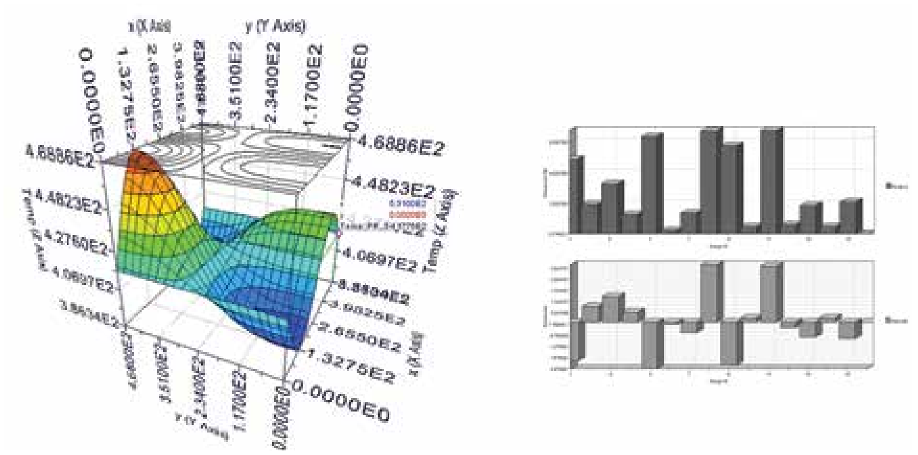


Figure 3.1.1 – Approximating function and error graph (relative and absolute errors respectively)

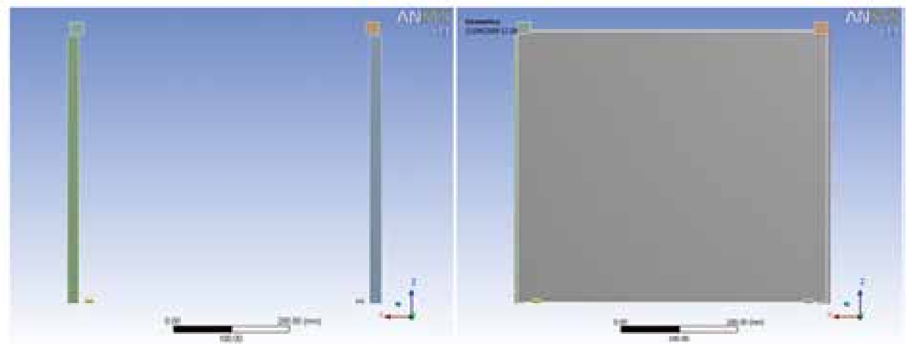


Figure 3.1.2 – Constraint system of the glass

3.2 FEM Model
During the FEM modeling process, free glass deformation was evaluated firstly, or the maximum deformation reached without any constraint.
During the next step, a series of constraints was applied on the glass, in order to compare the real glass deformation with the simulation and to estimate the model reliability.

3.2.1 Free glass deformation
By using ANSYS Multiphysics as finite element solver, only a corner was bonded and thermal field was applied in order to allow any deformation due to the thermal gradient.
The thermal gradient originates from a difference in temperatures between contiguous areas; to perform the analysis we should know the values on both glass sides.
The door of the oven is composed of three glass sheets spaced by few millimeters to allow an air cooling passage, this eliminates the installation of probes on the internal sides of the glass.
To obtain all necessary temperature values and to perform our analysis, we had to model the whole multiple glass system, considering convecting effects; the known temperatures were from the measured set on the first internal glass face and a reference temperature of 60°C was established.

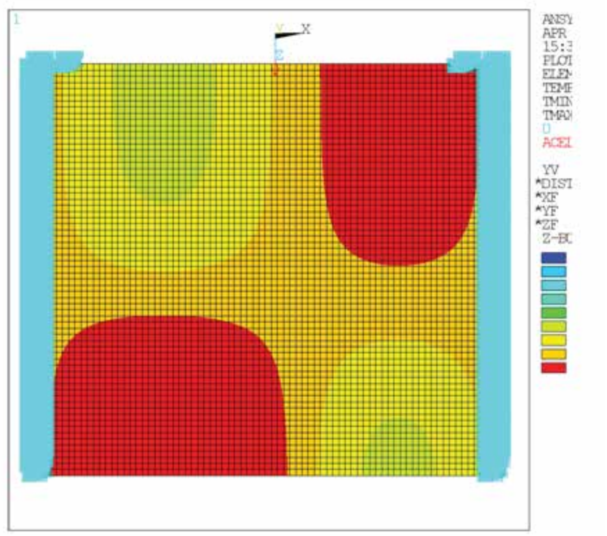


Figure 3.1.2 – Glass surface with the applied node-temperature

Once the estimated necessary temperature values were defined, we have modeled a single bond on an edge of the glass. We knew that this was an unfeasible solution but it was necessary to understand the entity of the maximum glass deformation with this temperature field.
By applying the calculated temperature function on the first glass, simulating heat transfer from the oven cavity to the room and calculating the thermal gradient on the component, we were able to obtain the maximum deformation of the glass in free conditions.
The results show that the maximum deformation is concentrated in the center of the glass, as expected. The value of this deformation is aligned to the experimental results.

3.2.2 Constrained glass deformation
The initial complete model has been simplified in order to speed up the simulation, as detailed in par. 2.1.
The constraints applied to the internal glass for the simulation of the real condition are:
- Upper support
- Side support
- Back support
- Lower support

Picture 3.1.2 illustrates the constraint system with and without glass. The upper support block YZ glass displacement, the side support block XZ displacement and the lower support block XY displacement. The constraint conditions have to be understood with a little tolerance in displacement. In fact, every constraint allows a clearance to avoid stress concentration due to an over- constrained condition.
Applying the temperature field to the modeled system as described before, we continue with the structural simulation to calculate the stress on and the deformation of the examined component.
In order to avoid value distortion, due to mesh problems, instead of considering maximum and minimum values, we have taken into account a mean value of this quantity close to the glass constraints.

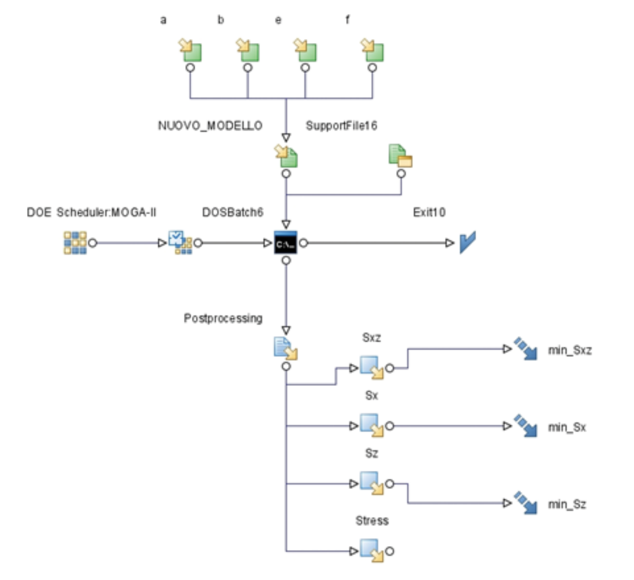


Figure 4.1.1 – modeFRONTIER's workflow

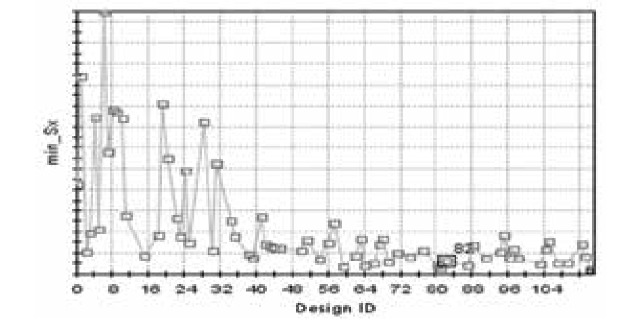


Figure 4.2.1 – History chart SX

4 Optimization of the glass support
The initial model described previously has been parametrized to allow the management by modeFRONTIER; the described parameters refer to the dimensions of the upper and lower glass constraints. While we focused on these constraints, the distances from the left and right glass edges and their width were parametrized.

The aim of this step was to define an optimum set-up of the constraint system that minimizes the glass deformations in pyrolysis conditions.

4.1 Project set-up in modeFRONTIER
Variables used in this first optimization sub-step are therefore four and each couple refers to the dimension of a constraint. The constraints on the glass are four, symmetrical, and hence it is sufficient to modify the dimensions of only one to modify the couple: these will be the variables of the optimization.
Lower and upper bounds of all the variables were set according to the customer's requirements.
By using modeFRONTIER, we want to manage the entire FEM (ANSYS) process automatically, to obtain the desired results.
To interface the FEM model with the optimizer, some macros were built, or rather a series of pre- and post-processing instructions to modify the geometry of the model during each simulation.
During the set-up of the optimization, some factors, such as time for each calculation or maximum available time have to be taken into account in order to define the best strategy.
In this project, the time for each calculation was about 75 minutes, not negligible; this made us choose a genetic algorithm that has a good robustness to find the optimum.
The objectives were:
- Minimization SXZ shear stress;
- Minimization SX normal stress;
- Minimization SZ normal.

The chosen algorithm was the MOGA (Multi Objective Genetic Algorithm), starting from an initial random population (DOE) of the input variables domain.
Simulation parameters:
- MOGA iterations: 10
- DOE dimensions: 12 - variables number multiplied for objectives

With these settings we have to do 120 runs for a total run time of 150 hours

4.2 Optimization results
After the optimization process, a good convergence of results was achieved: values of shear and stresses decreased up to 40% with respect to the original configuration.
Picture 4.2.1 shows an example of the history charts of stresses SX.

As this is a multi-objective optimization, optimum results are more than one: in fact, we could have some designs which achieve the first objective, but are very far from the other objectives. Hence we are looking for the best tradeoff!

In this job, all three objective are very correlated, so the convergence is parallel, which allows us to choose two optimal designs.

From the obtained results we can extract some important information about the component behavior in real working conditions, especially with regard to the glass constraints dimension and their dispersion across the oven door:

- Distance of the lower constraint from the edge of the glass seems to have no influence on stresses;
- Width of lower constraint should be bigger than original;
- Distance of the upper constraint from the edge of the glass seems to have no influence on stresses;
- Width of upper constraint should be smaller than original.

In summary, for an optimal solution, the constraints layout should encompass the upper constraint going more close with the opposite behavior for the lower constraints. In the following picture the optimal solution is graphically represented.

For the stresses, without having sufficient information about the glass characteristics, it is more opportune to present the deformation chart of the glass, during the pyrolysis phase.

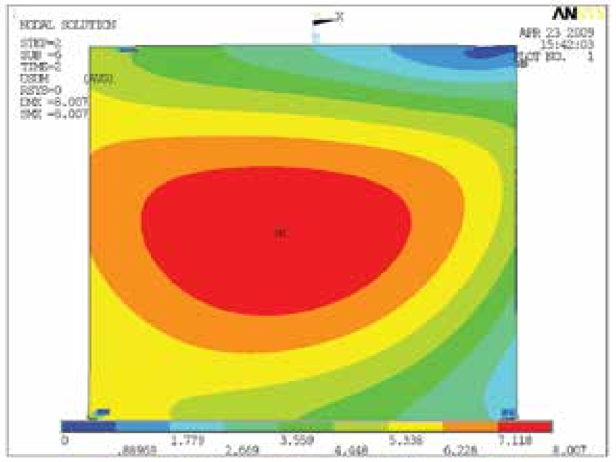


Figure 4.2.2 – Displacement sum

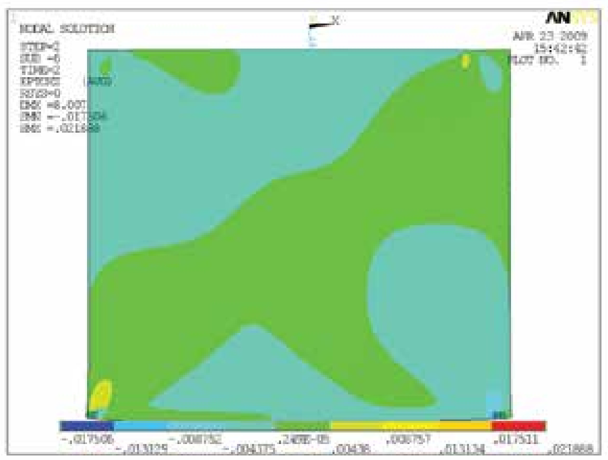


Figure 4.2.3 – Elongation due to the shear SXZ

5 Conclusions

The provided model is composed of an assembled system of three glasses, mounted on a chassis that keeps them separated to allow an air passage between them, in accordance with the regulations for this appliance.

Experimental tests performed by Indesit are focused on temperature measurement of pre-determined points located on the internal side of the first glass, in pyrolysis conditions, when the internal temperature of the oven rises to 500°C.

Punctual values of temperature, were computed with response surface modeling in modeFRONTIER in order to obtain a function that describes the temperature distribution on the entire glass, and assigns a relative value on each FEM model node.

The built map is related to the hot side of the considered glass. To calculate temperature distribution on the cold side, the entire glass system was modeled by thermal analysis. Knowing the internal cavity temperature distribution, the safety temperature on the external side of the outdoor glass and convex thermal coefficients, we were able to obtain the temperature distribution on the coldest side of the most stressed glass and hence also the thermal gradient applied to this component.

The focus of the first simulation was on examining the free constraint condition of the glass, or to verify the maximum deformation of the glass, without constraint.

In the subsequent simulations, the initial configuration, as described in the initial 3D model, was modeled with the dual purpose to validate the FEM model with experimental results, and to determine stress and deformation values of the initial configuration.

The aim of the optimization process was to find an optimal layout of the constraint system that minimizes stresses on the internal glass. To achieve this result, the FEM model was parameterized by means of a series of instructions named "macros", to allow modeFRONTIER to manage the geometry of the model.

The task of modeFRONTIER is to modify the model geometry on each run and to drive the input variables to the best set.

The modified parameters are referred to as the upper and lower glass constraints dimension, and in particular, the reciprocal distance and the width of each constraints are verified.

The results were the values of stress and deformation on the model, due to the thermal gradient applied. Due to imperfections in the mesh, the mean value of stresses close to constraints, was taken into account.

Obviously, the selected area for the calculation of this mean, was related to the area affected by higher stress values, to be precautionary.

The obtained results meet our expectations: a sensible decrease of stresses was registered nearby 30-40% with respect to the customer configuration, and a good conversion of results was achieved, highlighting the good quality of the work performed by modeFRONTIER.

The deformations of the optimized configuration are bigger than the original ones, which is an indication that the obtained design provides room for a better movement for the glass.

Finally, we are certain that the obtained results are sufficient and correct, and that this work has delivered further information and details about the system behavior to the modeFRONTIER users at Indesit Company.

Francesco Franchini, EnginSoft

World partner in high efficiency comfort

ARISTON THERMO GROUP

One of the world's leading companies in thermic comfort, Ariston Thermo offers a complete range of heating and water heating products, systems, services and solutions designed to provide the maximum degree of comfort with the minimum use of energy. Ariston Thermo, founded in 1930, is the Italian company with the widest presence in the thermic comfort around the world and over the 89% of its turnover is generated abroad. Its world-class manufacturing capacity, together with excellent pre- and after-sales support, offers an optimal combination of comfort, energy efficiency and respect for the environment. Ariston Thermo is present in three different sectors with leading brands and an extensive range of products and services: thermic comfort, burners and components.

Ariston products are conceived in order to meet the modern life needs: a wide offer of boilers, water heaters and intelligent air conditioners, together with a integrated range of solar systems and heat pumps water heaters, allowing the customer to take advantage of renewable energy sources. The group aims at generating the 80% of its business out of high efficiency solutions, also using renewable energy within 2020.

Using mode FRONTIER in design

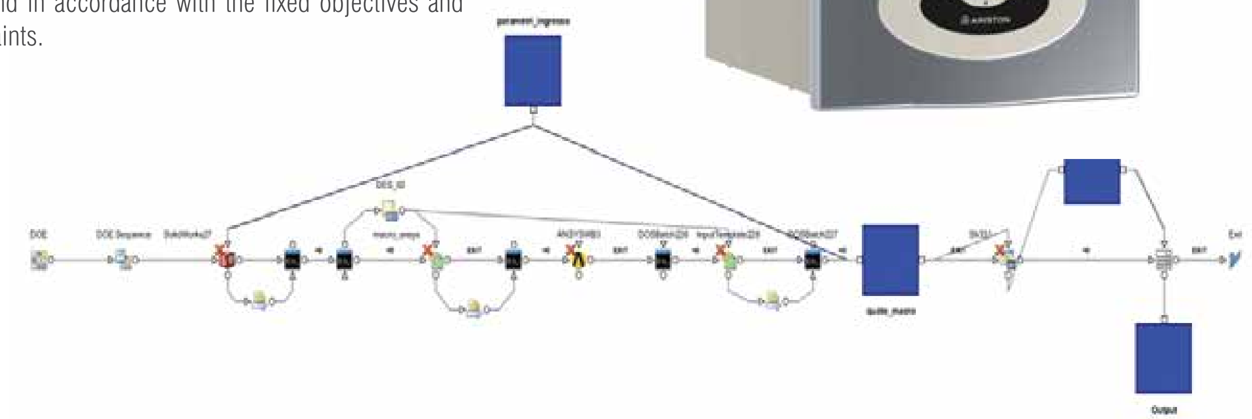
Ariston Thermo has always aimed at innovation and excellence as main goals for its growth and success; in the R&D context this approach is evident in the constant need for developing and obtaining always new and more performing products.

In the last years we have reached and overcome ambitious goals and kept on growing according to the main financial indicators, and not only, despite the difficult economic context. We are always looking for new challenges and "Excellence" is the key-word describing our approach. New investments will be also dedicated to improve our industrial footprint and oriented to research and development activities, so to make our solutions more and more efficient and sustainable.

The collaboration with our suppliers is a crucial element to achieve excellent results. In this context we have chosen the multi-objective and multi-disciplinary optimization platform modeFRONTIER, so to obtain, thanks to EnginSoft's support, the excellence we are looking for also in the design phase of our products.

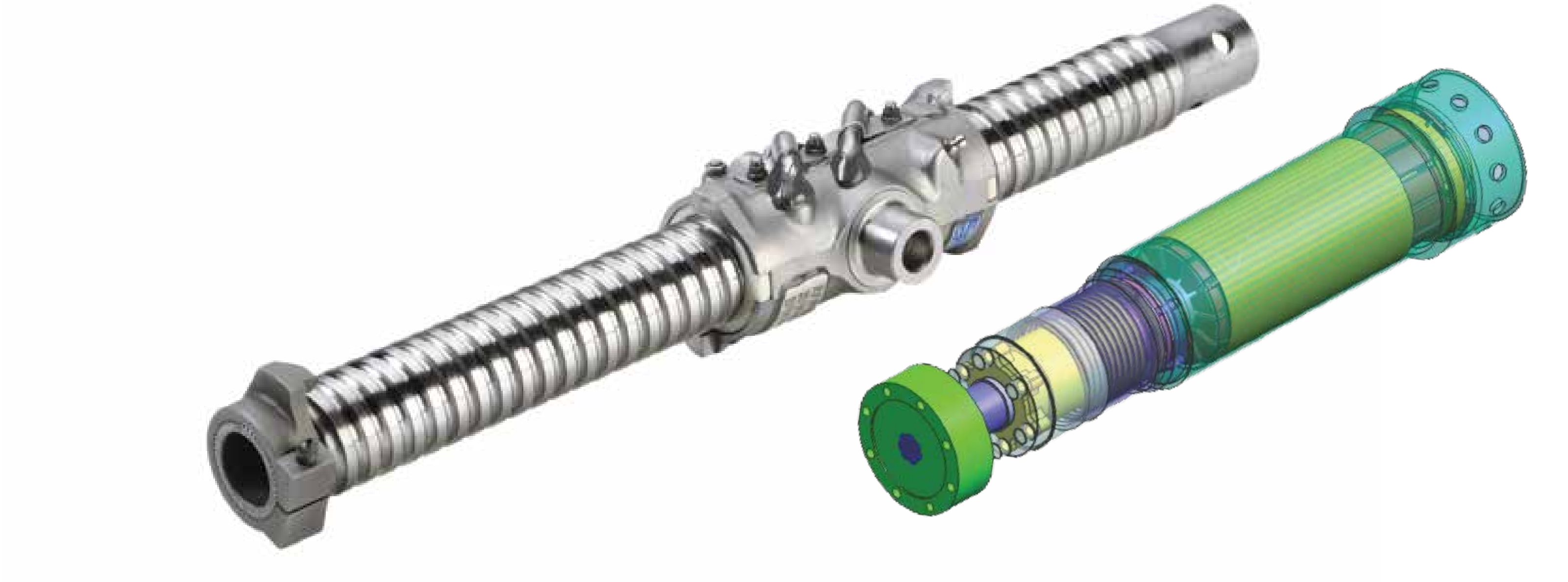
Roberto Mottola
CTO - Ariston Thermo Group Spa

It has been therefore necessary to introduce a new technology as modeFRONTIER in the complex design processes.
This MDO (Multi-disciplinary Design Optimization) platform allows to manage, in a fully automatic way, the product development processes or part of them, thus integrating the different software technologies used in the company, such as SolidWorks for CAD and ANSYS Workbench for CAE. Thanks to its numerous DOE (Design of Experiment) and advanced optimization algorithms, to the surface response methodology, to the robust analysis, to decision-making support and to its post-processing tools, which are available in modeFRONTIER through a user-friendly interface, the user has the possibility to vary the characteristic and geometric parameters of the product in order to obtain the best possible performance. Having the chance to formalize and drive the optimization process in a structured way, enables to face more and more complex and multi-disciplinary problems, if necessary, when a considerable number of parameters, objectives and constraints are involved.
The introduction of modeFRONTIER inside the design and development process of Ariston Thermo has allowed a full automation of the workflow, to take the most out of the hardware and software resources of the company and to reduce to the minimum the manual intervention, therefore dramatically decreasing the error possibility in any step of the activity carried out by the R&D group. This new work methodology has allowed to sensibly reduce the computation time of the project and to achieve the best possible solutions in the same time and in accordance with the fixed objectives and constraints.



VIRTUAL PROTOTYPING AND APPLIANCE APPLICATIONS

A clear strategic orientation towards quality and innovation determines the appliance companies' actions and development. They rely on their outstanding products and the added value that they provide to the customers in terms of performance, convenience and user-friendliness. Thus they create the prerequisite for long-term customer satisfaction and the basis for people's. Protecting the environment and the climate is an integral part of the strategy of the appliance industries, in the last years: energy- and water-saving household appliances make a significant contribution toward conserving resources. The increasing of know-how over the years and the partnership with CAE consultancy companies, help to set new challenging global standards on the environmental protection front and the responsible handling of resources too. In order to achieve this demanding goals is necessary a new methodological approach by means of modeFRONTIER which is able to manage multi-disciplinary and multi-objectives processes in order to develop new products that respect the environmental and performance requirements.



UMBRA: for high technology markets

We have been using the software ANSYS for several years and nowadays, considering the excellent outcomes of a pilot project, we have decided to rely again on EnginSoft and its software solutions, buying modeFRONTIER. We are convinced about the fact that our choice will be a successful solution for our needs and in respect with the Umbra Cuscinetti's policy, whose aim is investing in the best technologies since ever. Thanks to modeFRONTIER we have noticed a noticeable growth of the performances and a time and cost reduction.

Federico Perni
Technical Director - Umbra Group

UMBRAGROUP

Umbra Group's mission is to supply their customers with ball screws, bearings, as well as high technology electromechanical components and systems. In the last years, the Umbra Group has consolidated its position in the market and its philosophy is based on three principles: customer satisfaction, company's portfolio consolidation and harmonic growth of the company. The Umbra Group headquarters are set in Italy, Germany and U.S.A. and they cooperate with each other with enthusiasm and professional ethics in order to face the market challenges.
The Umbra Group operates in the following fields, such as: aerospace, industrial and biomedical applications, bearings, electric spindles and milling heads.
Thanks to its several experiences in the development of new technologies, the Umbra Group has become an important society within the aerospace industry and since its manufacturing has won a remarkable success the society has been pushed towards more advanced and reliable technologies.
The ball screws have been enhanced beyond expectation thanks to a new kind of steel with high level fatigue and resistance to corrosion performances and a ball patented architecture. Besides the aerospace field the Umbra Group is also to be considered, thanks to its comprehensive suite of components, a global supplier in the field of linear motion, that meets the most different customer demands.
Ball screws are mostly used to solve specific applications, such as high linear axial velocity, positioning precision, high accelerations, high push loading, and vibration reduction for extremely long screws. As regards the biomedical sector, Umbra Group aims to extend technical knowledge and the most advanced technology in the world in the field of linear motion to high performance biomedical tools.

modeFRONTIER in the design process

Recently, a design of an electro-mechanical actuator (EMA) for an active damping system has been developed: in particular, it is an innovative concept of actuator based on ball screws for short runs and high loads. This system allows a reduction on equal dimensions of the torque, that is necessary to enhance the specification loading: this represents a typical multi-objective problem, because at the same time the torque, the actuator dimensions and the inertia of the rotating components should be minimized, and these objectives can conflict with each other. modeFRONTIER has taken into consideration about 4000 designs to find the final optimal design.
Finding a solution to the problem that was impossible to solve after the designer's feasibility analyses has been made possible following the chosen parameters to perform the design. Finally, this study has led to a patent application.

Mechanical optimization of the injection system in a Compression Molding Machine

I wasn't an experienced modeFRONTIER user, so I found the Optimization Wizard very useful: it supported the choice of the number of designs, of the algorithm and of the number of iterations according to the time available for the whole analysis.

Andrea Minardi
CAE specialist at SACMI Packaging Division

The machine under study is a Continuous Compression Molding (CCM) hydraulic press for plastic cap manufacturing with extrusion of dry-blend granulated compounds. The machine performs the metering, the pelleting and the insertion in the cavities of the molded resin in order to obtain the final shape which is a semi-finished cap.

Figure 1 - a) Original 12 mm Piston. b) Broken Piston

The CCM machine is made of the following components: controller, extrusion, electric box, cooling box, molding module. The machinery has two carousels: one for completing the molding of the resin and one for executing the injection of the cavity. The latter performs the portioning of the melted pellets, the transportation and the compression inside the mold. In the injection phase, a pneumatic piston will insert the melted pellet into the mold.

The pneumatic piston is the component which we will investigate in an optimization approach that we present in this article.

A critical aspect of the problem is that the compression phase to complete the piston movement only lasts fractions of a second, two milliseconds for ascending and two milliseconds for descending - this allows a maximum production capacity of 600 Pieces per Minute.

The main consequences are high speed results and huge accelerations which can lead to potentially harmful collisions.

The first optimization procedure was completed by manually changing the shape of the piston in the configuration with a 12 mm diameter, in order to prevent occurring fractures as shown in Figure 1.

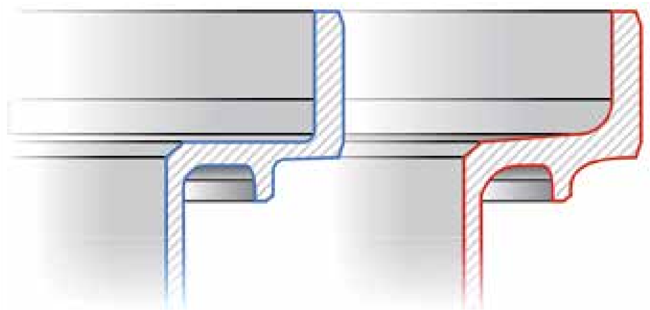


Figure 2 - Tapered Geometry (RED)

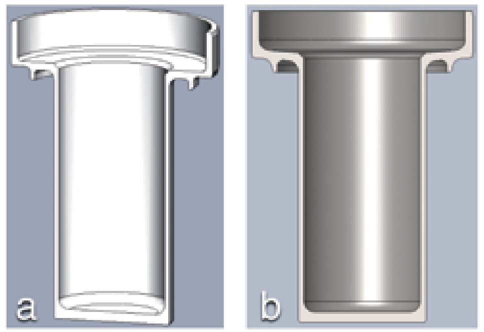


Figure 3 - a) Original geometry b) Manual optimized geometry

Geometry	Minimum Safety Factor
ORIGINAL (before)	0.9
MANUAL OPTIMIZED (after)	1.2 (+33.3 %)

Table 1 - Comparison Before and After the manual optimization

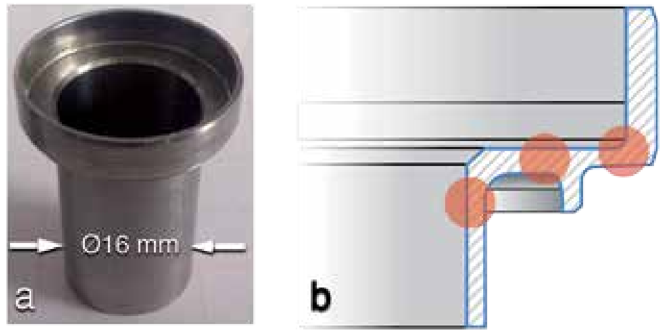


Figure 4 - a) 16 mm piston with original geometry b) Critical regions (RED)

The design activity was carried out using SolidWorks (from Dassault Systèmes) as geometry modeler and ANSYS as Finite Element Method tool.

The manual optimizations followed the mechanisms of intake and exhaust valves inside endothermic engines, where the right shape configuration of tapered surfaces is essential for improving performances. In this way, the piston region where fractures generally occur, was modeled through a tapered geometry (see Figure 2).

The solution for the design problem required a trade-off between the reduction of weight and an increased safety factor, both could be achieved with a stress analysis. The increase of the weight of a high-speed moving component led to damages in some surrounding areas.

For this reason, we decided to design a light yet strong piston. After 20 working days, the manual optimization had to be terminated due to difficulties we experienced in achieving further improvements in the performances of the part. The results are summarized in Table 1 and in the Before and After Geometry comparisons (Figure 3).

In the next phase of the study, the new component to be optimized was a 16 mm diameter piston that was initially sketched with the same original geometrical configuration (not tapered) of the 12 mm piston (before the manual shape optimization). In this configuration, the piston features some potentially harmful regions for the fatigue analysis as illustrated in Figure 4.

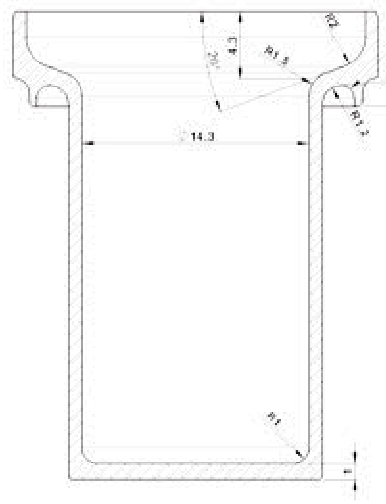


Figure 5 - Free geometrical free parameters

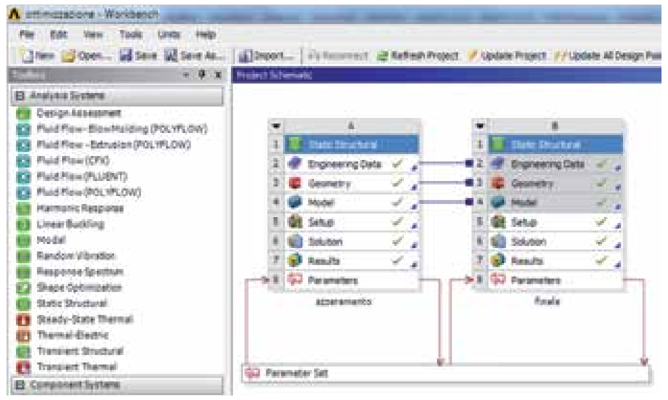


Figure 6 - ANSYS Workbench simulation layout

In addition to the geometry modeler (SolidWorks) and the FEM tool (ANSYS), an optimization tool has been adopted (modeFRONTIER). The idea is to use modeFRONTIER for schematizing the design process and for defining an optimization strategy.

The first step was to prepare a parametric geometry of the piston in order to transform the most relevant model entities into design variables that can be managed by the optimization Environment. Figure 5 shows the two-dimensional draft sketches and the nine parameters that control all the possible piston shapes. The problem is solved in two dimensions because its axial-symmetric characteristics also allow a consistent reduction of simulation time.

The second step of the automatic optimization set-up was to create a FEM model starting from the parametric geometry. Here, Workbench from ANSYS has been used as it allows the designer to lay-out the simulation process. In our present case, two simulations had to be performed (see the scheme in Figure 6): the first should solve the stress generated by the collision of the piston (on the left), while the second (on the right) represents the final run of the analysis that will supply the simulation results to modeFRONTIER.

The final step of the optimization procedure is to define the objectives and constraints along with the strategy to be used for the search of the optimum. The modeFRONTIER workflow shown in Figure 7 reflects the entire process in a single diagram: input variables (on the top), process integration and optimization strategy (in the middle), output variable, objectives and constraints (at the bottom).

With regard to the adopted strategy, an initial set of configurations was needed for initializing the optimization algorithm. The wizard of the optimization tool provided the proper choice of methods in order to pursue the objectives in a time frame of 24 hours.

The system selected the SOBOL Design of Experiments of 50 starting points (designs). Then a Multi-Objective Genetic Algorithm was used for achieving the two design objectives, the Maximum Principle Stress (X axis, see Figure 8) and the Minimal Principal Stress (Y axis, see Figure 8). The constraints were provided by the acceptable weight tolerances (+ - 10%) towards the original design.

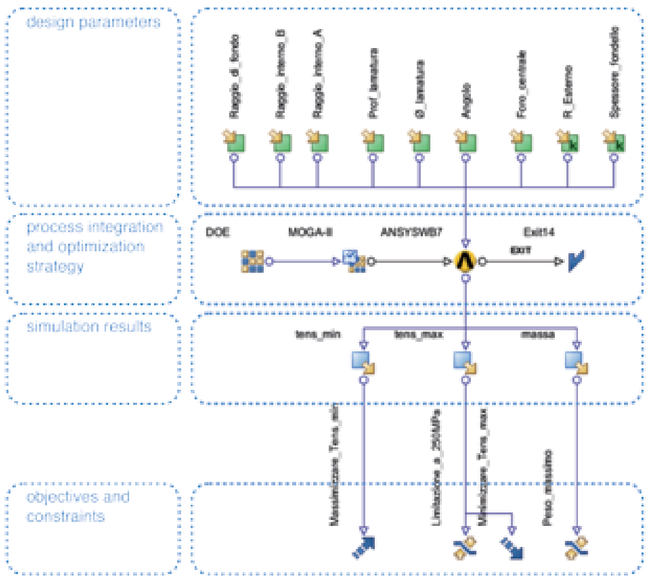


Figure 7 - modeFRONTIER design optimization workflow diagram

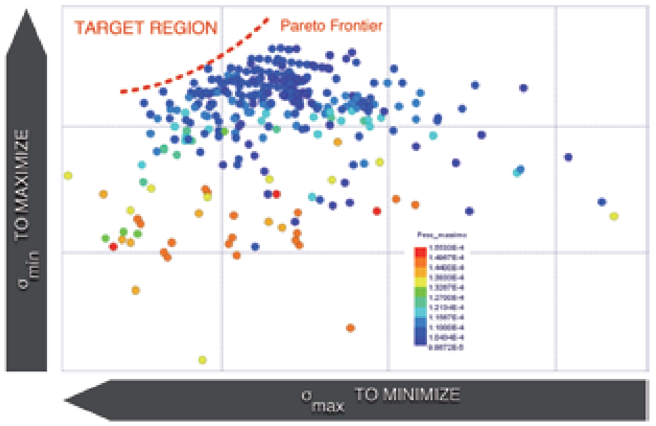


Figure 8 - Scatter chart displaying the 800 results of the automatic optimization process

The optimization successfully completed 800 different piston configurations (which are graphically represented by a bubble in the scatter chart in Figure 8, the color scale is associated with the weight of the piston (from blue to red).

The scatter chart also presents the Pareto Frontier which contains all the optimal designs (Pareto designs). It is possible to operate the trade-off between the piston configurations within the designs. This is a subjective choice that has been carried out in order to select the final design obtained through an automatic optimization procedure (see Table 2). The optimal piston selected for the comparison with the original one is shown in Figure 9. With modeFRONTIER it is also possible to obtain statistical analysis results across the design variables. The statistical plot in Figure 10 shows the direct and inverse relationship between the problem variables. More specifically, it features in colors (from red to blue) and numbers (from 1 to -1) the correlation between the input parameters and the output measure. For example, by increasing the internal diameter of the piston it leads to a consistent (0.77 means high direct relationship) increase of the Minimal Principal Stress and an even greater (-0.99) reduction of the total mass of the piston.

Figure 9 - Original 16 mm piston (LEFT) and Optimal piston as result of automatic optimization process

Geometry	Minimum Safety Factor
ORIGINAL (before)	0.9
MANUAL OPTIMIZED (after)	1.3 (+44.4 %)

Table 2 - Comparison Before and After the automatic optimization on the 16 mm piston

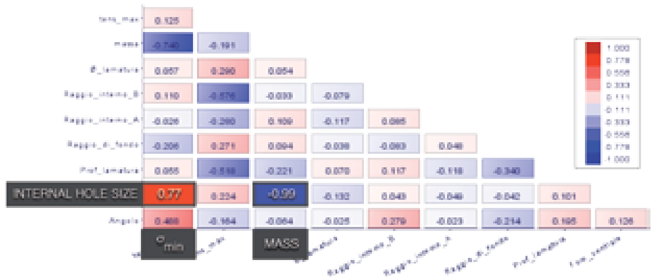


Figure 10 - Correlation Plot

Conclusion

In conclusion, we can say that we have obtained a sufficient improvement on the 16 mm piston while substantially saving time for completing the tasks. Moreover, by adopting a design framework as the one provided by modeFRONTIER, the designer can focus more on the pre and post-processing of the optimization results. It is no longer necessary to change, again and again by hand, each parameter at a time for increasing the safety factor of the component under study. This leads to a better exploitation of the design cycle time (as illustrated in Table 3) and to an optimal solution, both through objective optimization and subjective selection of the best compromise among the available results.

Andrea Minardi - SACMI Group
Francesco Franchini - EnginSoft

	MANUAL OPTIMIZATION	OPTIMIZATION WITH modeFRONTIER	OVERALL OUTCOMES
VIRTUAL ANALYSES TESTED	about 30	800	**+2667%** better exploitation of simulation resources
PERFORMANCES IMPROVEMENT	+33.3 %	+44.4 %	**+33%** better results
TOTAL TIME TAKEN TO COMPLETE THE TASK	20 days	4 days	**500%** better exploitation of design time

Table 3: Comparison between manual and automatic optimization.

Multi Variate Analysis in Systematic Impeller Design Applying modeFRONTIER at Sulzer Pumps

The most important pump component - its heart - is the impeller which transforms kinetic energy into pressure and therefore generates the required head. The impeller geometry is defined by more than 50 parameters requiring experienced hydraulic design engineers. Even if only 20 of these parameters have a major influence, it is obvious that a severe variation yields an excessive database which should be made use of.

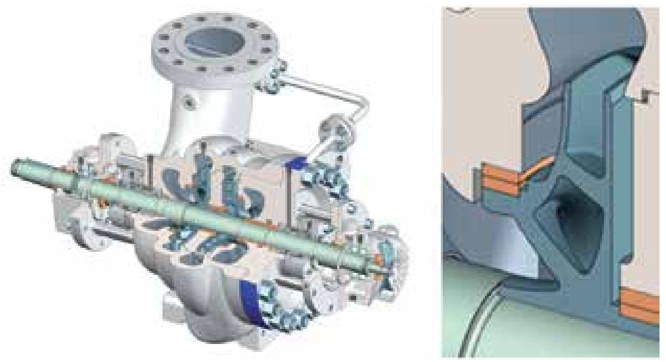


Figure 1 - Two stage pump with detailed view of the first stage impeller.

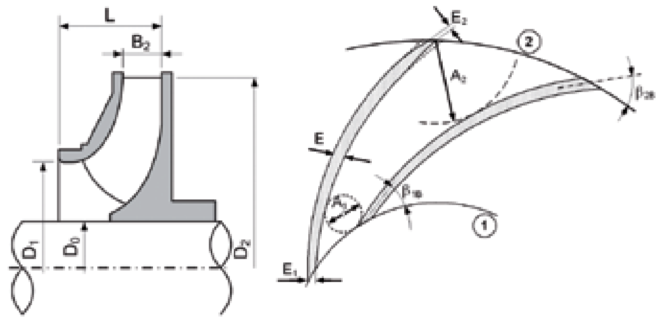


Figure 2 - Dimensions of the impeller.

A proper classification of the available designs in the database gives the developer a better understanding of the complex parameter correlation and enables the prediction of not yet available impellers by interpolating among the existing designs. This gives a first parameter estimate for the new impeller and properly conditions the variable ranges for an optimization which is likely to follow. This article presents an approach based on classification of existing impeller designs with Multi Variate Analysis through Self Organizing Maps (SOM) by use of modeFRONTIER.

Systematic impeller design

The parameters defining an impeller include the main dimensions like outer diameter D_2 and shaft diameter D_0 as also the meridional contour and blade shape (Figure 2). The impeller design is done for a specified operating point with given flow rate Q and head H for a certain rotational speed n. Efficiency η is one criterion for an optimal impeller design not only at best efficiency point bep but also over a certain operating range (Figure 3, left). Suction capability, which is the pressure available at pump inlet NPSH, is another criterion (Figure 3, centre). Decreasing NPSH affects the pump head which needs to be considered.

Good suction capability and high efficiency both over a broad operating range are conflictive design goals. Increasing suction capability at maximum operating point reduces efficiency at minimum operating point. This is an important fact when using optimization techniques in impeller design.

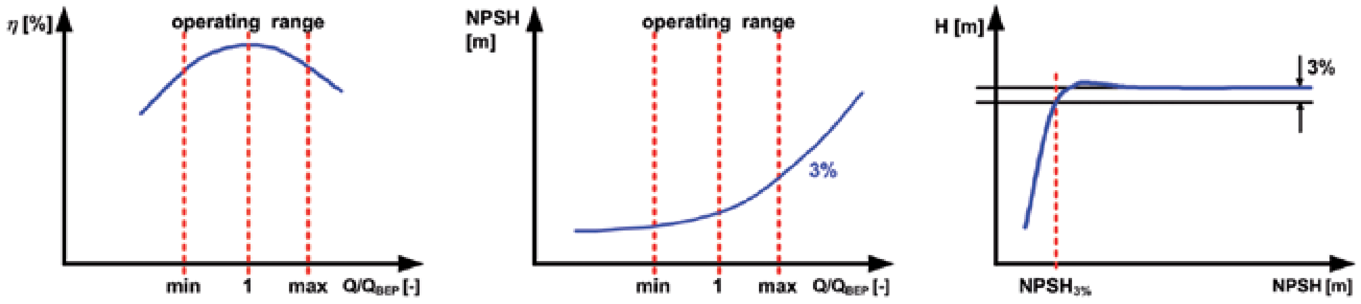


Figure 3 - left: Efficiency η; centre: suction capability NPSH within the operating range of the impeller dependent on the flow rate Q; right: NPSH3% criterion

Characteristic numbers

Impellers can be classified by characteristic numbers enabling a comparison among the designs. The specific speed n_q defines the form of the impeller (Figure 4) and is calculated from flow rate Q, head H and the rotational speed n. Figure 5 lists the main design parameters and shows their conversion into characteristic numbers. The outer diameter D_2 of the impeller is selected according an optimal head coefficient ψ for the specific speed n_q. The inlet diameter D_1 influences the suction capability and depends on the flow coefficient at inlet φ_1. The suction capability can either be expressed by a characteristic number σ or the suction specific speed n_{ss} which both depend on the suction head at pump inlet NPSH. Similar relations exist for other dimensions.

Using these characteristic numbers and dimensionless values, impellers with different outer diameters D_2 can be compared and new designs can be calculated based on these values. This facilitates a classification of the impellers and the use of the SOM technique.

Self-Organizing Map

Any existing impeller design is described through a multi-dimensional vector, where each component represents a defining parameter (input) or a performance index (output).
The Self-Organizing Map (SOM) is an unsupervised Neural Network algorithm capable to group and classify such already available impeller designs in a two-dimensional grid space. Each node of this grid is called "Unit" and it groups (includes) vectors (impeller designs) that are similar with respect to all their parameters (inputs and outputs) simultaneously.
SOM preserves the topology of the data, so that similar data items will be mapped to nearby units on the map. To do so, units are hexagonal-shaped, and hence each unit has 6 neighbors and is labeled by a "prototype vector" that in fact represents all the vectors included in the unit itself, as a kind of average. SOM lives in the multi-dimensional data space, but its visualization capabilities are built on the top of its representation in the grid space. Each of the hexagons becomes a "pixel" being colored to reflect different properties of the input data, e.g. specific speed n_q, impeller width B_2 or efficiency η. This way SOM overcomes the problem of visualizing multivariate data: input data are projected onto a 2D grid (Figure 6).

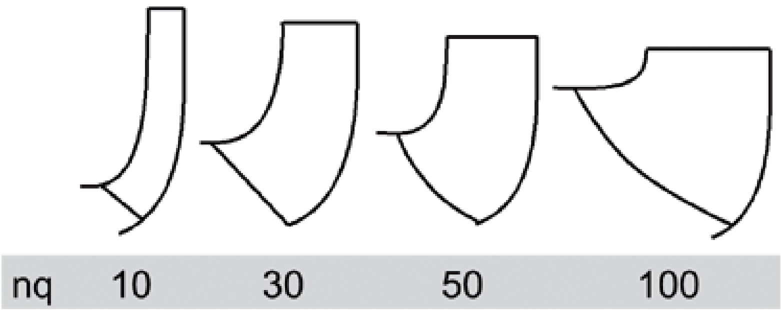


Figure 4 - Impeller form in meridional view dependent on specific speed n_q

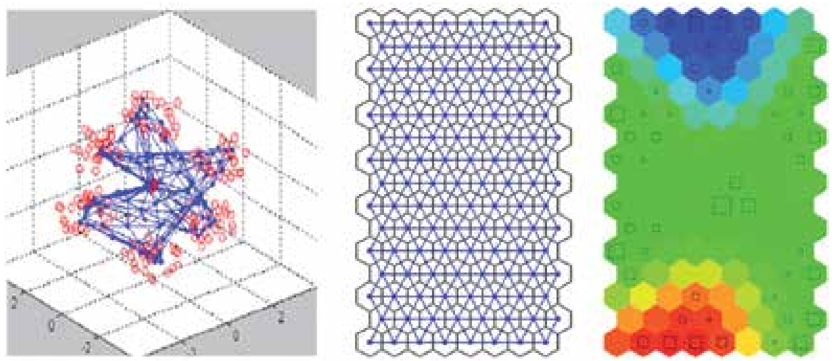


Figure 6 - Left: SOM is the blue network that adapts to real data (red points) in a X-Y-Z space, note that some nodes are far from any real point, hence the related unit will be empty.
Centre: the same SOM in its 2D conventional representation: each of the nodes is a hexagonal unit. Right: each unit is colored with respect to the X-value of its prototype vector, and the square on its center represents the number of real design enclosed in the unit (see the empty units).

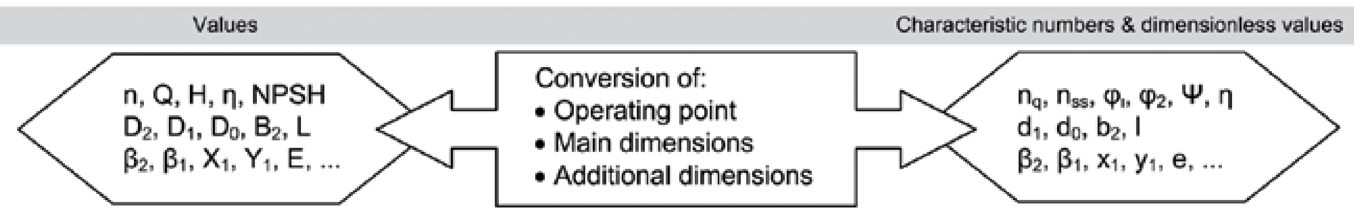


Figure 5 - Correlation between dimensional and non dimensional values

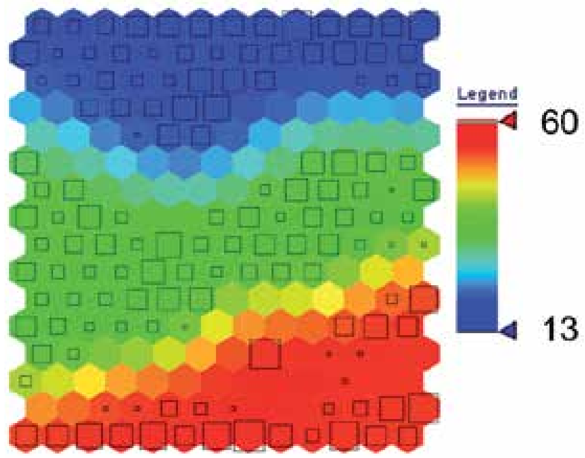


Figure 7 - Specific speed (n_q) in the SOM with distribution of existing designs

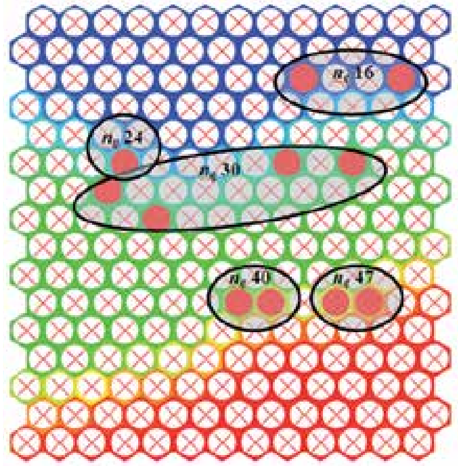


Figure 8 - Selected designs in the SOM (Color: specific speed)

Another advantage of the SOM is related to its intrinsic interpolation capability. There might exist regions of unexplored zones, the performance of the impeller is not yet predicted by CFD. This is reflected in SOMs by empty hexagons separating others that are filled up by different families of designs. When this happens, it is reasonable to look at the prototype vector of the empty unit as kind of forecast of a design family that have still to be realized, and that represent a reasonable interpolation of the ones that are available. The benefit of the SOM is that, apart from the input variables characterizing such design families, also a complete forecast of the performances is immediately available. This predictive use of the SOM is really powerful when handling designs that are described by a high number of parameters (inputs and outputs) so that any other interpolations approach, like Response Surface Modeling, becomes heavy to implement.
For the pump impellers described here, a unique SOM is trained on the existing database and used to forecast new design families able to provide certain performances.

Impeller design and multi variate analysis

The dimensionless values for the main parameters and the design objectives efficiency and suction capability (η, $n_{SS,bep}$, $n_{SS,max}$) are selected as input for the training (classification) of the SOM. Within this test case, the results of six different impeller optimizations with three different specific speeds between n_q13 and n_q60 are used as data basis. Goal of this study is to develop new impellers in this range with high suction capability and high efficiency for four different specific speeds (n_q16, n_q24, n_q30, n_q47) under the assumption that for each n_q both operating point and impeller diameter D_2 are given and the shaft diameter is pre-defined from mechanical calculations.

Figure 7 illustrates the trained SOM of the specific speed ranging from n_q13 (blue) to n_q60 (red). The squares describe the density of input parameters available. The larger the square the more data exists, no square signifies that parameter values are based on pure interpolation. The selection of the new impellers is undertaken in regions with purely interpolated data (Figure 8). For each new impeller, existing designs with a similar n_q in the SOM table are compared. This is necessary as three objectives need to be fulfilled, and the SOM designs might only achieve one.
The advantage of this technique is the access to every single parameter defining the impeller geometry. With an amount of over 50 parameters, the entire meridional impeller contour and the blade shape are approximated by the SOM. This method allows a complete impeller design within a few minutes just by giving the operating point and selecting an appropriate outer diameter D_2. The impeller parameters are taken from the SOM and converted back from dimensionless to dimensional parameters. A new impeller is then generated with the conventional design tools and its performance is checked by CFD.
Table 1 shows a comparison of the performances obtained by CFD and predicted by SOM for the selected n_q. A coefficient is defined with:

$$objective_{CFD} / objective_{SOM}$$

describing the ratio of the CFD result to the prediction of the objective by the SOM. A value equal to one signifies an error of zero; the CFD performance matches the predicted one.
For a coefficient smaller than one, the performance is over predicted, if it is larger than one, the design is under predicted by the SOM.

n_q	Design characteristics	η	$n_{SS,bep}$	$n_{SS,max}$
16	higher efficiency	1.011	0.995	1.112
16	lower efficiency, better suction capability	1.012	1.068	1.101
24	One design only	1.024	1.071	1.213
30	lower suction capability at max. OP	1.019	1.117	0.76
30	higher suction capability at max. OP	1.006	1.036	0.453
30	lower suction capability, lower efficiency	1.003	1.058	1.191
30	higher suction capability, lower efficiency	1.029	1.046	1.203
47	lower suction capability at bep	1.149	0.975	1.078
47	higher suction capability at bep	1.109	1.024	0.793

Table 1 - Comparison of coefficients of obtained and predicted objectives for the selected designs

n_q24

The first impeller modeled with the SOM is n_q24. Therefore the best possible solution in compliance with the specific speed and the design goals is selected. CFD calculations are performed according the CFD in the optimization process. The results are excellent, both efficiency and suction performance are better than predicted by the SOM.

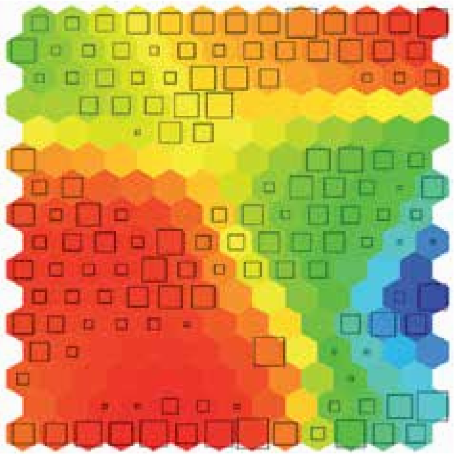


Figure 9 - Efficiency (red = high, blue = low)

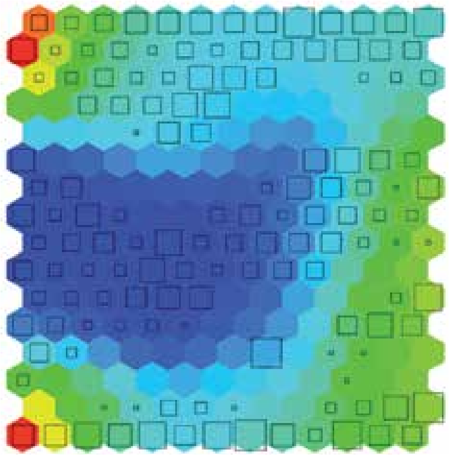


Figure 10 - suction capability at bep (based on σ, blue = good, red=bad)

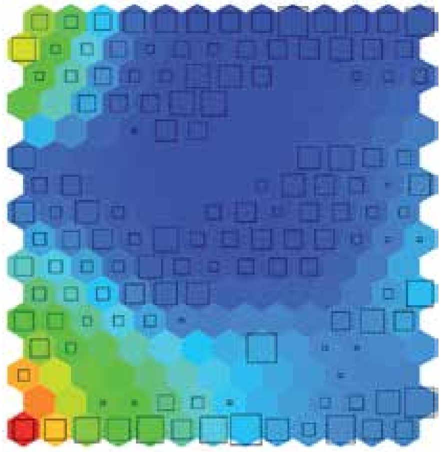


Figure 11 - suction capability at max OP (based on σ, blue = good, red=bad)

n_q16

For the second impeller (n_q16) two different designs are selected from the SOM table, one with high efficiency predicted and a second with a lower efficiency but a better expected suction capability. The impeller with high efficiency reaches almost the suction capability at bep while the impeller with the lower efficiency exceeds the suction capability. Both impellers outperform the expected suction capability at the maximum operating point efficiency.

n_q30

For the impeller n_q30 two different interpolated designs are selected from the SOM table, differing in suction capability at maximum operating point. After calculating performances of the interpolated designs, the aspired suction capability at overload is not achieved, the other targets are outperformed. For this reason two more designs from the SOM table are selected, now with lower efficiency than the previous designs. With the lower efficiency target, the suction capability is reached for both operating points. This proves the conflicting design targets efficiency and suction capability.

n_q47

Two designs from the SOM table are selected. The second design with the higher suction capability target at bep misses the required suction capability at maximum operating point. Even if the first design does not fulfill the requirements at bep, the deviation from the target value is only small.

Summary for all designs

For all designs, the calculated efficiency is higher than SOM predicted. The suction capability misses the requirements for some designs because of contradicting objectives. In these cases it is possible to select new designs from the SOM with compromises in efficiency but achieving the required suction capability.
Figures 9-11 present the objectives efficiency, suction capability at bep and max OP. It can be clearly seen that efficiency and suction performance pattern are completely different. This discrepancy makes it difficult to fulfill all three objectives and either a compromise is required or one objective has to be prioritized.

Conclusions

The article describes a novel methodology to design impellers starting from the well assessed knowledge at Sulzer Pumps. The concept has proven to provide the designer a new and effective tool to speed up the design process of the pumps core part - the impeller.
Self-Organizing Maps (SOM) have been trained on the already available impeller designs and corresponding performance indicates: such a SOM embeds the so far available pump designer knowledge, and provides a complete interpolation in regions in which designs are still missing. Each input or output variable of the impeller design can be represented through a conventional two-dimensional SOM map. This allows the use of SOM as an extremely powerful tool to suggest new designs in regions in which the design space has not yet been explored to forecast their performances. In fact, the methodology allows a new and complete impeller design in some minutes, just assigning a few parameters, as the operating point and the outer diameter. Any new design proposed by the SOM can be validated through high-fidelity fluid dynamic simulations (CFD) and then be used as starting point for further refinements by directly linking the CFD model to a modeFRONTIER optimizer.

Sulzer Pumps

Sulzer Pumps is one of the world's leading centrifugal pump manufacturers. Intensive research and development in fluid dynamics, process-oriented products and special materials as well as reliable service helps Sulzer Pumps maintain its leading positions in its key markets. Its customers come from the oil and gas, hydrocarbon processing, power generation and pulp and paper sectors as well as from water distribution and treatment and other general industries. The products are internationally reputed for their technical excellence.
www.sulzerpumps.com

Wolfgang Maurer, Susanne Krueger - Sulzer Pumps
Luca Fuligno, Francesco Linares - EnginSoft

Bonfiglioli: a complete range of gearmotors for industry

Bonfiglioli

Bonfiglioli Riduttori SpA designs, manufactures and distributes a complete range of gearmotors, drive systems, planetary gearboxes, inverters and photovoltaic solutions to satisfy the most challenging needs in the fields of industrial automation, mobile machinery and renewable energy. Bonfiglioli offers tailored solutions, whose strength lies in the advanced content of each product and the intelligent integration of different technologies.
As a leader in global power transmission and control, Bonfiglioli is committed to satisfying its customers' requirements by supplying high quality products and providing excellent service on an increasingly wide scale.
Bonfiglioli has always worked in order to integrate the complex requirements of growth and productivity generated by its development. The essential element of its strategy has been the creation of market-oriented business units, able to design tailored solutions meeting customers' needs. The four business units namely are: Industrial (with mechatronics and power transmission divisions), Photovoltaic (also focused on regeneration solutions analysis) Wind and Mobile.

After having considered the best alternatives available on the market, we have set up a pilot project in collaboration with EnginSoft with the aim of accurately evaluating modeFRONTIER so to avoid any possible risk; the results of such activity have fully satisfied our needs also thanks to EnginSoft expertise and competence in this sector.

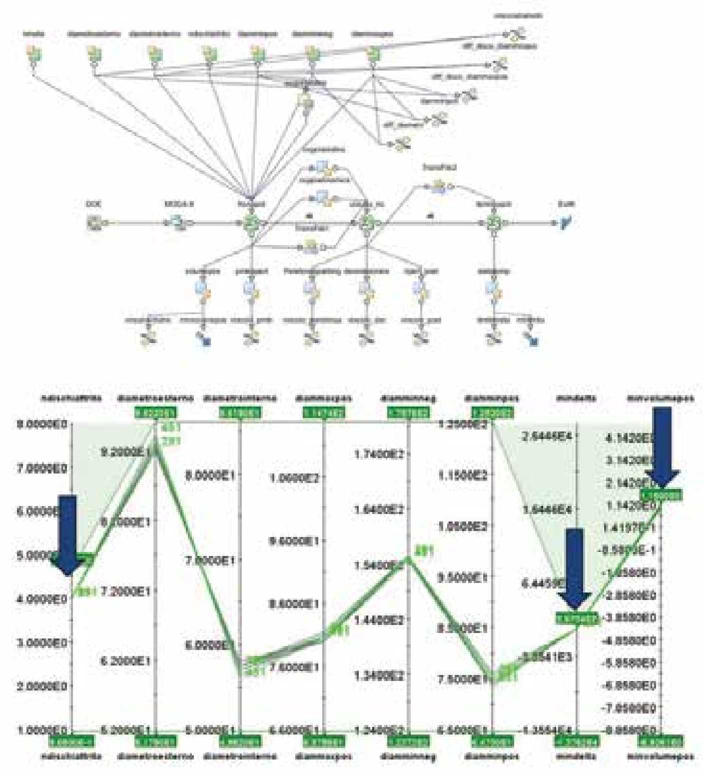
All in all, we are confident of our choice which is the best solution on the market and in line with Bonfiglioli Riduttori SpA style, oriented to invest in the best technologies so to offer its customers always innovative solutions, in accordance with market requirements.

Andrea Torcelli
Research and Development Manager
Bonfiglioli Riduttori Spa

Why modeFRONTIER in design

The pilot project we have focused on in Bonfiglioli has been developed considering one of the recurring applications related to the performance optimization of a braking system. The project was selected also considering the possibility of integrating a MDO tool in the design and analysis flows of the company. The main objective of the project was that of determining the optimum geometric configurations of the braking system, able to guarantee also the best performance from a thermal and dynamic point of view in accordance with the design constraints and specifications.

The analysis procedure, managed in Bonfiglioli using complex Excel sheets, has been integrated and fully automated within the modeFRONTIER multi-disciplinary optimization platform, which has allowed to easily manage different mono-objective and multi-objective optimization processes according to the user's needs. In this way, over 1400 different configurations of the systems have been automatically analyzed in a half a day time achieving improving results both in terms of system performance and in development time of analysis process. As far as the mono-objective problems are concerned, just few minutes are enough for a full optimization in comparison with the 4-8 hours required by the manual approach. In this way, thanks to modeFRONTIER, the optimum configurations in relation to the starting nominal conditions have been determined, obtaining an improvement ranging between the 18% and the 44%, depending on the different objectives. The customer has highly appreciated the possibility of automatically analyzing a huge number of configurations in the same time frame (from 10 to 1500), thus allowing a real and exhaustive exploration of the whole project space. The next and natural step will be that of integrating in the optimization flows the CAD and CAE tools traditionally used by Bonfiglioli to develop and analyze its products.



VIRTUAL PROTOTYPING AND MOBILE APPLICATIONS

The Mobile Business Unit has the know-how it takes to customise products and to ensure total satisfaction of customer needs, like as design and develop solutions for a wide range of user applications.

This vast experience has led to the development of gearmotors for travel, rotation and other specific applications. All products must be superbly reliable and respect the highest quality standards even in applications involving high levels of mechanical stress. The mobile markets are advanced markets, which are constantly evolving and require extremely close attention to design and construction. For this reasons the use of a new technology, as modeFRONTIER, within complex design processes and development is necessary to develop new products or enhance existing ones in order to remain competitive and able to face new market challenges.

Franco Tosi Meccanica: Innovation at engineering service

Franco Tosi Meccanica is nowadays a company leader in the design and production. Founded in 1881 by Franco Tosi, and with 130 years of market experience, the company has always had a core business focused on hydro turbines, stream turbines and powerful turbo-machines in general. In the nineties, Franco Tosi ownership was taken over by Finmeccanica Group and merged with Ansaldo Energia. Franco Tosi became an operating division of Ansaldo, dedicated to industrial stream turbines, compressors and heat exchange devices.

In 2001 the company was taken over by Casti Group and today Franco Tosi Meccanica has its majority controlled by Gammon and the company can autonomously operate in the sector of big machines for power generation, with a range of hydraulic and thermal products going from few to over 800MW.

Using modeFRONTIER in design

A group of designers and engineers has been very active in Franco Tosi for over 10 years, using ANSYS CFX simulation tools, together with in-house tools and procedures. In order to improve the performance of the ever growing energy sector, it has been necessary to analyze several multi-objective problems. For this reason Tosi has applied modeFRONTIER to the optimization of its most advanced components design, currently under development. In this way they could achieve a correct scheme of the input and output phases of the most relevant engineering variables. Furthermore modeFRONTIER has allowed to analyze the components of hydraulic and stream turbines, in order to obtain an optimal design, evaluating the qualitative and quantitative details, as well as understanding their effect inside the machine, through parametric analyses. Both quality and reliability have been improved, and these are the main characteristics of Franco Tosi Meccanica. Thanks to these tools, Franco Tosi Meccanica machines successfully operate all over the world, guaranteeing their customers excellent performance in terms of flexibility and engineering development.

We have been using ANSYS for many years now and after having collaborated with EnginSoft technical team for several engineering and training activities, modeFRONTIER and the multi-disciplinary competences of EnginSoft have proved to be very efficient in the integration of the optimization tools in a complex process and the iteration between fluid-dynamic and structural simulation, allowing to improve the product performance and finding the necessary compromise between conflicting objectives, as the complexity of the shapes required by advanced fluid-dynamics and structural resistance requirements. We have chosen modeFRONTIER to face the development of new turbines, trusting EnginSoft competence and sure that ANSYS and modeFRONTIER are indispensable tools to reach the ambitious targets of the market. We have estimated a significant improvement of the performance and an overall reduction of time and costs in the product development phase, thanks to modeFRONTIER.

Emanuel Pesatori
R&D Manager - Franco Tosi Meccanica

Solar Industry
Numerical Simulation and Optimization

Nowadays, the renewable energies attract a lot of attention from politicians and the public. On the one hand, this is a consequence of an increased environmental awareness all over the world. On the other hand, new technologies can become the best strategy to face and overcome the global economic slump. A loan of hundreds of millions of dollars provided by the U.S. Department of Energy to a solar panel company based in Silicon Valley, California, is another clear proof of the commitment and investments made in this field. Also, financial institutions and banks are ready and eager to invest in a promising sector with expectations for growing revenues. For instance, the fourth largest bank in the US, signed an agreement to fund SunPower, one of the most important solar panel manufacturers in the United States. Figure 1 illustrates the expected electricity generation scenario in the USA.

The main goal of the companies involved in this business is to develop new technologies to improve the efficiency and reliability of solar panels. This task is not at all trivial, since there is a relevant amount of parameters that affect the performances and the costs of the solar modules. Despite the fact that efficiency is crucial and that the multi-junction technology should reach a remarkable value of 40.8%, there are other very important factors needed to guarantee the commercial success of solar panels. Under this point of view, reliability, robustness, operational life, manufacturing processes and the use of materials can not be considered less important than the conversion efficiency. All these factors could dramatically affect the future of solar technology compared to others. In this context, only optimized solutions can stand out and survive.

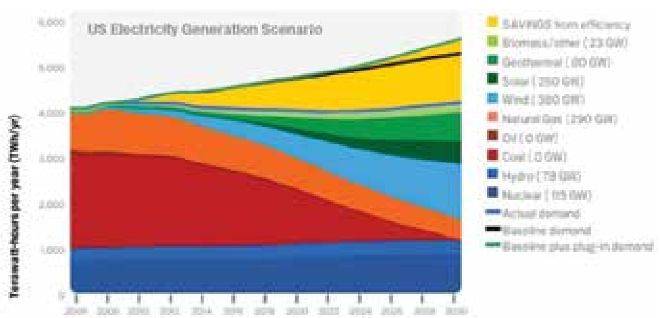
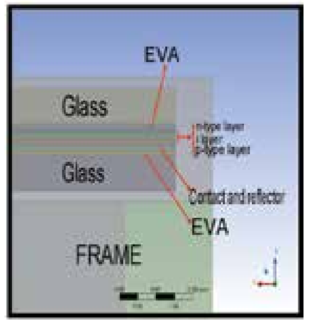


Figure 1- US Expected electricity generation scenario

Numerical simulations

In order to reach the optimum result, the first step is to acquire a deep understanding of the behavior of the solar panel. Numerical simulations are by definition tools devoted to investigate and evaluate the behavior of systems or their functional parts, allowing in this way, to improve the efficiency and to tremendously decrease the cost of the prototypes. This article describes a demo case, mainly focused on the evaluation of the mechanical performance of a solar panel. Some of the simulations executed have been performed in order to verify if the analyzed solar panels comply with EC Standard. A better understanding of the solar panel behavior has been achieved by performing not only mechanical analysis, but also fluid dynamics and thermal-electric simulations.



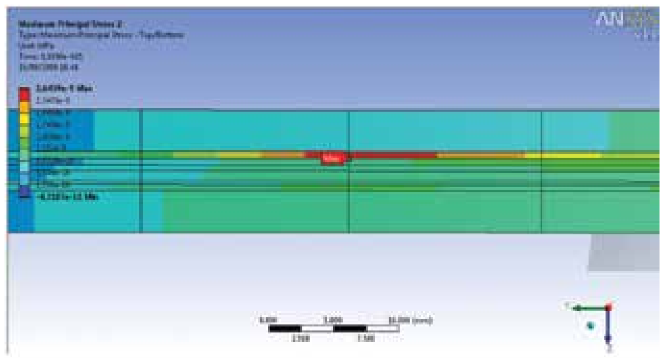


Figure 2 - Solar panel cross section - Principal stress

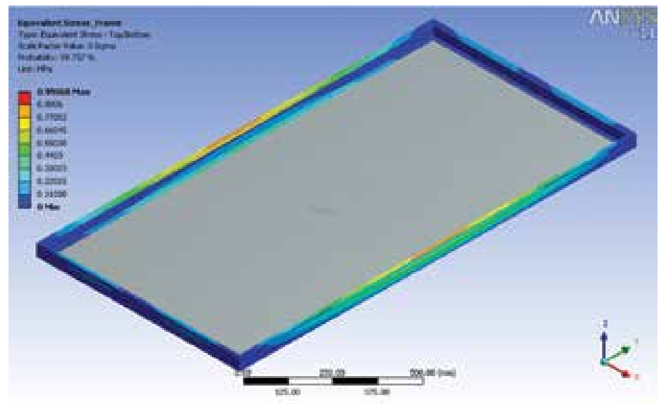


Figure 3 - von Mises stress induced by PSD

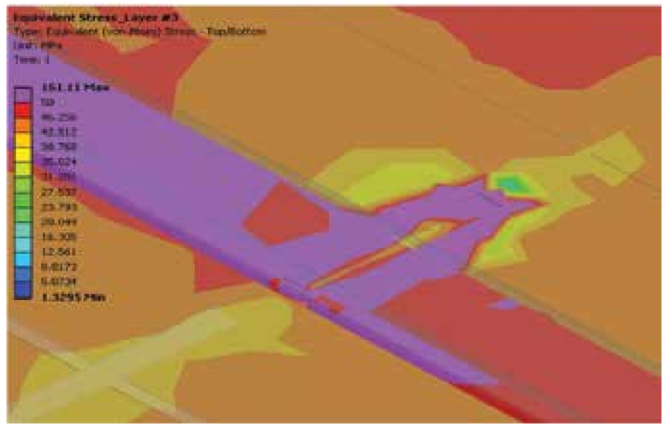


Figure 4 - von Mises stress induced by thermal cycling test

The EC Standard requires that solar panels are robust enough to resist hail impact. Following the standardized test, if a steel ball (1.18lb) was dropped from 51 inches, an approved panel will not crack. Since ANSYS Workbench R11.0 has been used to simulate the drop test, a command snippet was inserted in the GUI to set the explicit solution. Maximum principal stress, evaluated at the impact point on the glass layer, was 43MPa (see figure 2), lower than the breaking limit value. The new Release 12.0 does not need scripts for explicit analysis because of the new capabilities.

The second analysis evaluated the effect of a static load (400lb) applied on the top layer (glass) of the solar panel. In addition, a transient dynamic analysis has been performed to gain a deeper understanding of the structural behavior. The dynamic load has been applied as a transient sine function with a period equal to the first natural frequency of the panel.

In some particular cases, transportation may be a matter of concern because of the vibrations induced in this phase. This also pushed to evaluate the suitability of the modules to support random vibration loads. The analysis performed revealed that in all cases considered, stress levels are lower than the admissible values.

After installation of the solar panel, thermal conditions become a severe cause for mechanical stress, mainly on the solder connections. Because of the relevance of this issue, a thermal cycle test is required based on the EC standard. The standard test requires the sample to undergo thermal cycles from a low temperature of -40 °C, to high temperatures equal to +85 °C with a dwell time equal to 10 minutes at both higher and lower temperatures.

As expected, the junctions between cell and connector are the most sensitive parts with respect to the thermal cycle test. The following figure reports a detailed view of the stress spot.

High temperature is not only challenging from a mechanical point of view, but also considerably affects the electrical performance. It has been determined that the decrease in efficiency can beat 0.5%/°C (depending on the technology used), as high temperatures reduce the open-circuit voltage. Consequently, under severe sun irradiation conditions during the operational phase, the negative effects of high temperatures can result in bad performances. Because of the importance of this issue, a thermal-electric simulation on a single cell has been performed to analyze the temperature field triggered by the Joule heating induced by the current collected by the cell. Moreover, a fluid dynamic analysis has been performed in order to take into account the air flux around the solar panel to evaluate both the ventilation around the panel and the stress on the support frame induced by the wind pressure (see figure 5).

The analysis revealed that under a structural point of view, the frame support is properly designed to resist the standard code wind. From a fluid dynamic aspect, as expected, a low pressure zone was detected on the back side of the panel causing inefficient heat dissipation.

Optimization

Numerical simulations are a powerful tool to evaluate the performance of a design, but in a market where only the best technologies can survive, the optimization process plays a crucial role and is as important as numerical simulations. As explained above, the goal for manufacturers and researchers is not only to increase performances, but also to reduce cost and time of production, so that significant optimization can be achieved, from the early design stages to the final product manufacturing processes.

The original design has been optimized by modeFRONTIER, a multi-objective optimization software tailored to be coupled with other programs, such as, for example, Finite Element Methods or Computational Fluid Dynamics software (not only engineering software though). The main task of the optimizer is to drive the initial set of parameters that define the model, to the/an final optimized set of parameters which define a new better performing model. Basically, the optimization process is made by modifying the input variables, using mathematical algorithms, and analyzing the outputs in accordance with the objectives and constraints of the design.

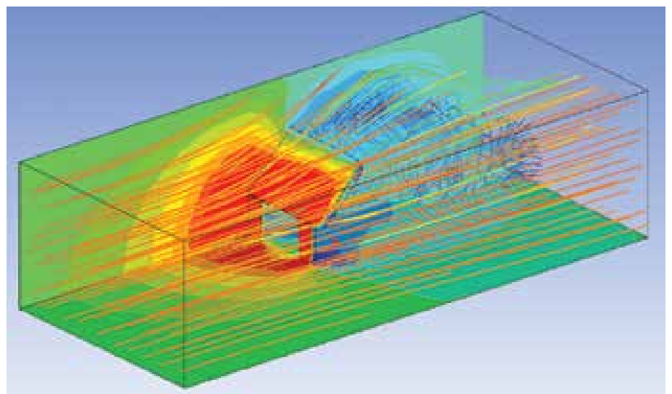


Figure 5 - Pressure Distribution and Velocity Streamlines

The first phase of the process starts with the Design of Experiments (DOE) to generate an initial population of possible designs. Starting from the initial population, modeFRONTIER explores all parameter domains. It searches for the maximum or minimum of the objective function(s) using a variety of state-of-the-art optimization techniques. An Optimization process, with many and conflicting objective functions, cannot deliver "the" optimal solution as a result, but rather a "full set" of optimal solutions called Pareto frontier. Each solution of the Pareto frontier maximizes/minimizes at least one of the objective functions, but none of them maximizes/minimizes all objective functions. This article presents two case studies. The first one is a multi-objective and multi-disciplinary optimization; the second one is a mono-objective structural rigidity of a solar panel mount optimization.

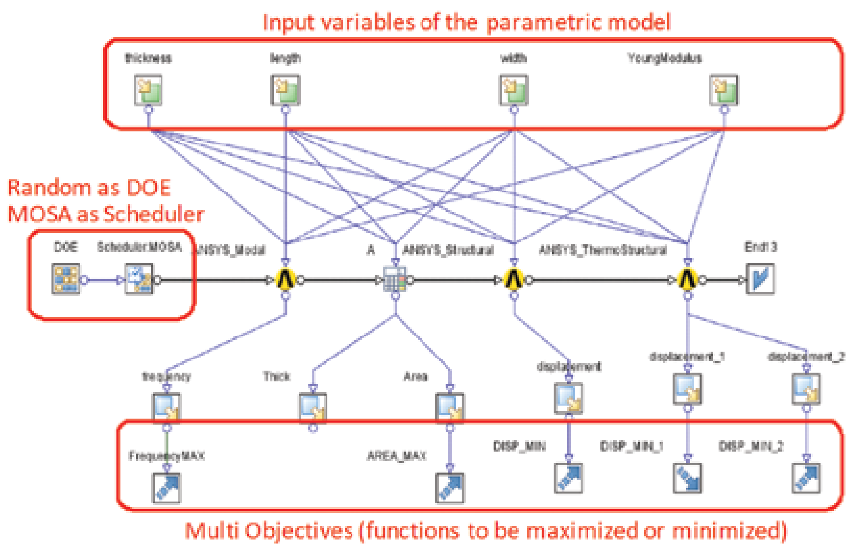


Figure 7 - modeFRONTIER Workflow

PARAMETER	VARIABILITY RANGE
Young's Modulus	6.0e+10 – 7.0e+10 [Pa]
Length	1300 – 1900 [mm]
Width	400 – 1500 [mm]
Thickness	-4.5 – -1.5 [mm]

Figure 6 - Input parameters and variability range

Solar panel case study. Multi Objective Optimization

Optimization Problem and Objectives

The structural and thermal behavior of the solar panel during the operational phase is determined by the geometric and material characteristics. Hence by modifying the geometric and material parameters, an optimum solution can be achieved.

We have searched for an optimum solution by maximizing/minimizing the following objectives:

- Maximize the exposure area to sunlight;
- Maximize the first frequency of the solar panel;
- Minimize the displacements due to thermal cycling;

The input parameters and their variability range which have been used in the optimization problem, are shown in Figure 6. Since the defined objectives are conflicting, a certain trade-off will be accepted. The finite element model has been generated and parameterized in Workbench R11 and the Optimization "Workflow" has been defined in the modeFRONTIER Graphical User Interface (GUI), as shown in figure 7. The GUI allows to control any process setting included in the optimization algorithm.

Evaluation of the optimization results

After the optimization algorithm has completed its process, due to the many objectives, several optimum solutions have been generated. At this point, a careful evaluation of the results is indispensable. Despite the fact that a "design table" provides all input and output parameters of the process, a comparison of the designs is necessary in order to understand the effectiveness of the optimization. A parallel chart can be used for this task. To speed up the post-processing, it is possible to

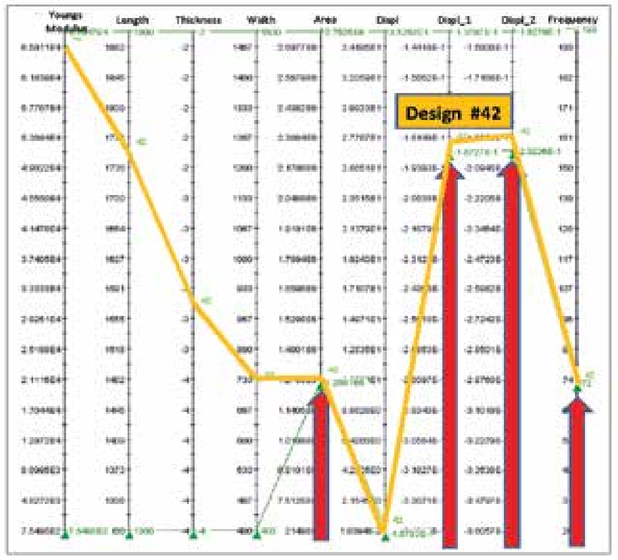


Figure 8 - Parallel chart

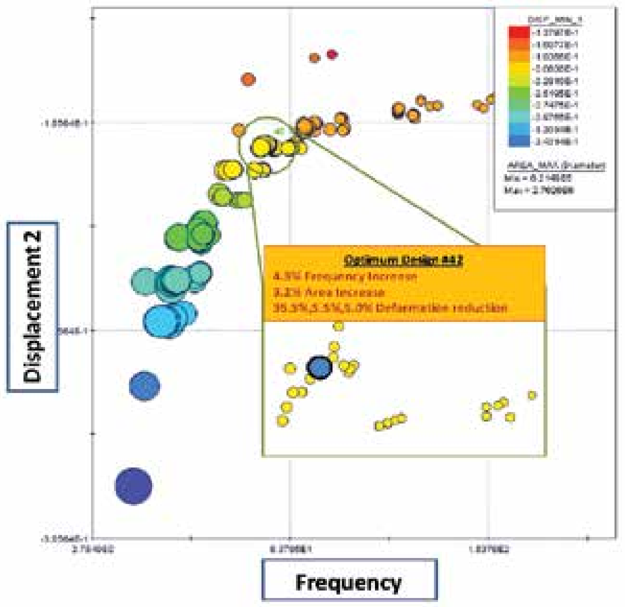


Figure 9 - Bubble chart

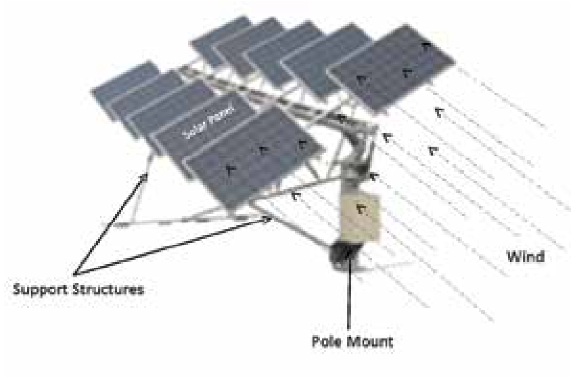


Figure 10 - Solar Panel with Pole Mounts Schematic Diagram

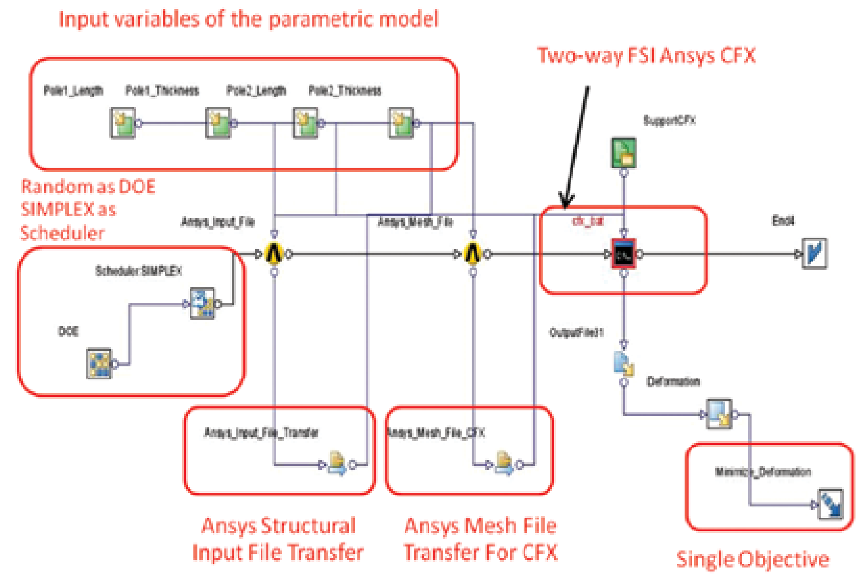


Figure 11- modeFRONTIER Workflow

work on the parallel chart output ranges, in such a way that a reduced subset of optimized designs can be obtained (see figure 8). To focus on the most relevant output parameters, a bubble plot has been used (see figure 9).

Finally, by merging the information provided by the parallel chart and the bubble chart, an optimum design has been selected. The improvements achieved are reported below:

- maximized power output (+3.2%)
- maximized robustness (+4.3% first frequency; -35.5% displacement)

Solar panel case study. Structural Optimization of the pole mount supports

The second case study analyzed has been focused on the structural optimization of the solar panel pole mount supports (see figure 10). The goal of this optimization case study has been to identify the best geometric configuration of the pole mount support structure when subjected to a wind load equal to 5 m/s. The analysis was performed with the aim to find the maximum displacement of the solar panel. Since the problem involved only one objective function, the optimization process is defined mono- objective. In order to generate the optimization workflow, ANSYS Structural has been coupled with ANSYS CFX. Consequently, a Two-way Fluid Structure Interface analysis needed to be performed. In figure 12, the optimization workflow is shown. The improvements achieved on the structural rigidity are equal to 56%.

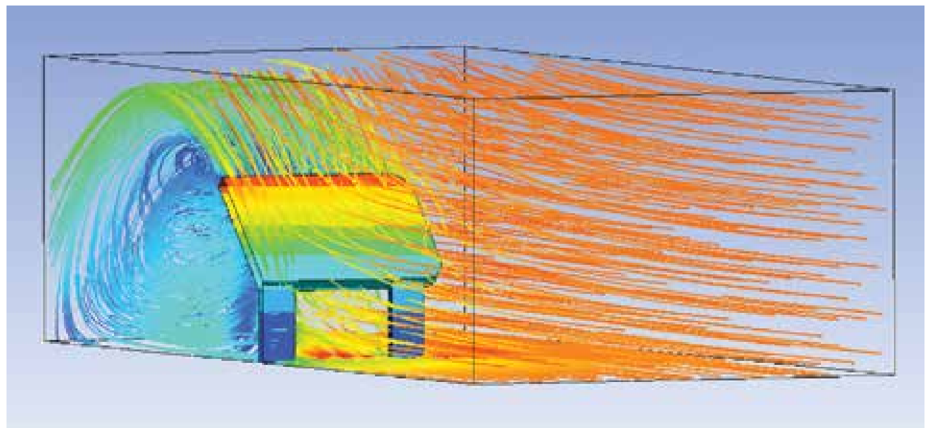


Figure 12 - Deformation and Air-flux Streamlines

Conclusions

In recent years, the interest in the solar industry, its developments and advancements, has been growing steadily; economic, scientific and technical sectors have contributed to this trend and process.

In this context, numerical simulations have proved to be mature, powerful and reliable technologies whose capabilities can be exploited to reduce cost related to test phases, to gain a better understanding of the behavior of solar panel systems, and to prevent possible causes for failure or low efficiency.

Furthermore, since the solar sector is expected to assume a major role in the global energy market, and specifically in domestic energy demands, the primary objective is to guarantee that solar panels deliver best performances in costs, efficiency, reliability, robustness, safety, durability and aesthetics. Existing difficulties for designers are linked to the huge number of parameters and the conflicting ways in which they affect the final results. In order to overcome these difficulties and to reach the targets, design processes have to take into account multi-disciplinary and multi-objective optimization techniques to achieve optimum results.

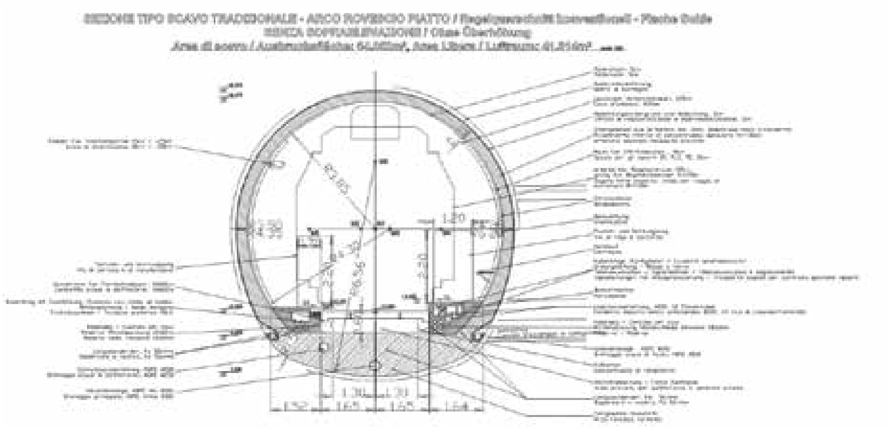
Nicola Varotto, Vijay Sellappan
OzenEngineering, Inc.

Design of the Brenner base railway tunnel

A relevant application of this optimization software to civil engineering

The Brenner base tunnel is one of the greatest engineering works of the 21st century. It is located on the AC Trans European railway line which links Italy to Germany. The tunnel track is 57Km long, with a southern connection at Fortezza train station and a northern connection at Innsbruck bypass. The cover reaches up to 1650m.

The main formations are crossed, from South to North, by granites, paragneiss, calc-shist, gneiss, marbles and phyllades.
The geological peculiarity is the crossing of the Periadriatic Line generated by the collision of the African plate with the European one.

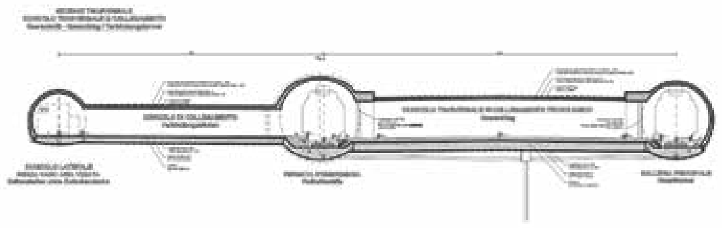


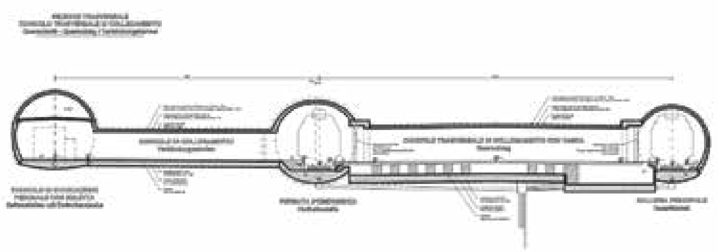
Geometric characteristics of the transversal section

The typical section consists of a single bore with a driving diameter of 9.6 m, where all safety, signaling an telecommunication devices are located. The drainage occurs due to gravity using a service tunnel located in-line with the two bores. Safety connection by-passes have been placed each 333m so to works also as technologic rooms.

Intermediate multi-function places

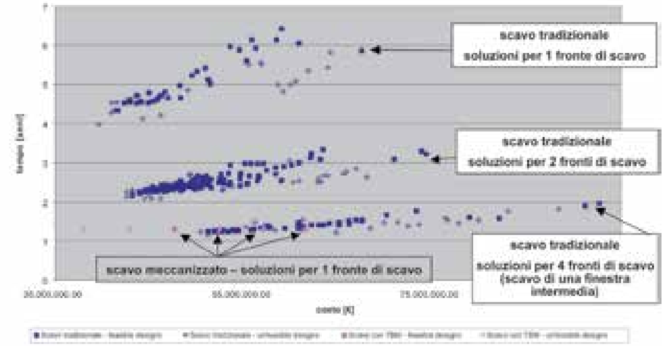
The safety concept is based on the creation of multi-function places (PMF), located at a distance not superior to 20Km. The PMF are characterized by the presence of safety tunnels, that allow ventilation and a safe evacuation in case of accident.

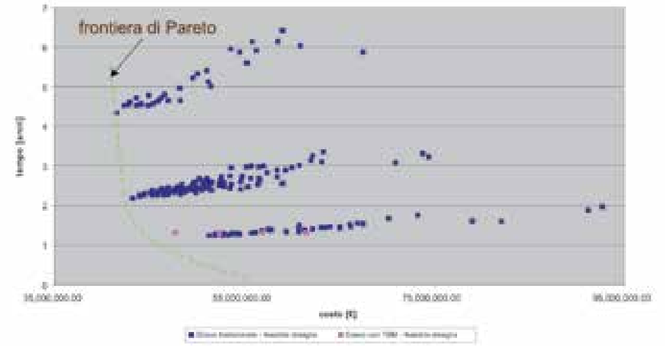




Design Analysis

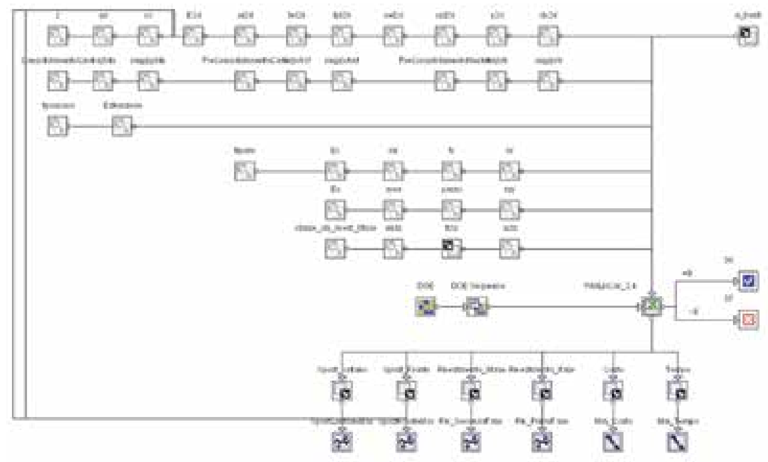
The investigation of all possible phenomena related to underground driving at great depth has required a considerable application of analytical models. The complex design of such a work has then needed the elaboration of FEM bi-dimensional models, located in the most critical sections together with some tri-dimensional FEM elaborations in correspondence to the PMF.





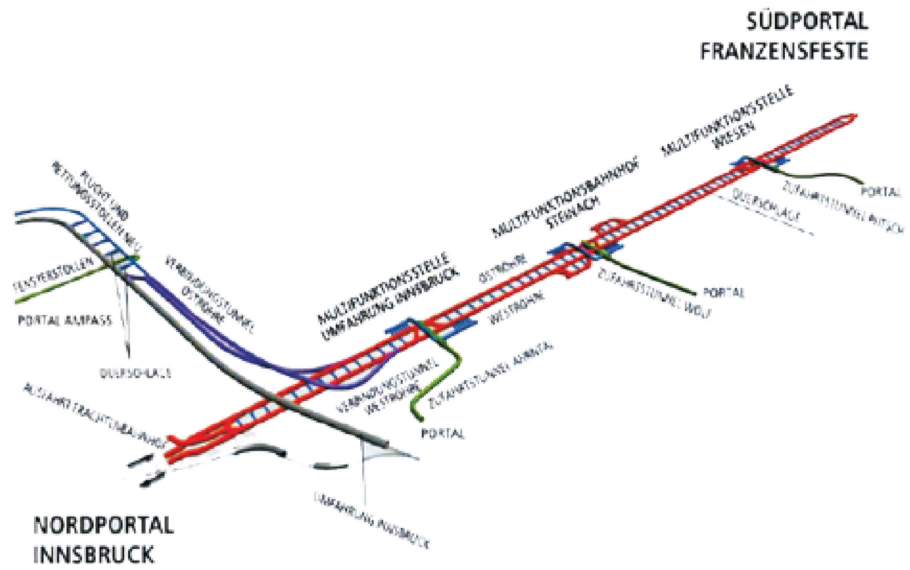
modeFRONTIER developments in underground works engineering

The design of the Brenner base tunnel has led expert technicians to face with problems of grat interest. The main unknown element in this kind of investigation has been represented by the uncertainty of which data have to be used in the models which should simulate the mechanic behaviour of the boulder at tunnel depth. In such a context, the deterministic approach is not always appropriate, since the unknown elements related to the parameters estimation of both the default behaviour model and the real behaviour model have to be taken into account. It' therefore preferable to apply a probabilistic approach, as it has been done for the Brenner tunnel, where the complexity and the uncertainties where extremely high due to lithologic variability, for boulder behaviour and behaviour model parameters.
The decision of using modeFRONTIER proved to be a successful one, considering the tool versatility, the richness in options and the particular structure available for data synthesis and representation, which is extremely useful for the designer engaged in a decision-making process under uncertainty conditions. The tool has been firstly used to verify in which way the model response varies when simulating the mechanic behaviour of the boulder in relation to the input parameters variation. The most important data of the problem, the existing correlations and, generally speaking, every useful information related to the decisions to be taken and the safety margins have been identified.



The obtained data have been therefore assumed in order to evaluate the optimum driving techniques. Furthermore, the designer could take great advantage of this investigation in further debates, due to the technical synthesis possibilities and results visualization available in this tool with great efficacy and in an engineering style.

Stefano Fuoco - SWS Engineering



Genetic Algorithms in the Optimization of Cable Systems

In recent years, cable-strut assemblies attract a lot of attention from engineers, due to their versatile shapes, their lightweight and architectural impact. Cable-strut structures have become popular as roofs for arenas, stadiums and sport centers. Yet their working principle is not so easy to understand since they can carry loads thanks to prestress, so that their behavior under loads must be studied taking into account, at least, the geometrical non-linearity. For these reasons, design experience and intuition may not be enough when engineers work with cable systems.
In this article, the matrix theory of a generic three-dimensional pin-jointed structure is first referred. Then, by using modeFRONTIER, a general method able to provide a design solution, which is not only technologically sound, but optimal with respect to the design requirements, is applied to the design of a Geiger Dome.

Introduction

A structure, with a new particular shape cannot be considered as an innovation just because it is very complex. An innovation is a new system working with new mechanical principles, for a better use of materials, lightness etc. Cable-strut assemblies are not an innovation because they are truss systems that are well-known for centuries. However, their last development - the tensegrity systems – can be seen as a real innovation (Motro, 2003). In these systems, the geometrical shape and the prestress in the elements play a crucial role in the structure stability. The first civil structure inspired to the tensegrity principle is the cable dome proposed by Geiger and first employed for the roofs of the Olympic Gymnastics Hall and the Fencing Hall in Seoul (Geiger et al. 1986). The largest existing cable dome is the Georgia Dome designed for the Atlanta Olympics in 1996 (Yuan et al. 2003).
In this article the design of the cable systems is explained, and the Geiger Dome is used as an example.
Particular emphasis is put on a particular optimization procedure, based on a genetic algorithm. This allows us to find a design solution that is not only technologically sound, but optimal in the design requirements (Biondini et al. 2011). The genetic algorithm of the modeFRONTIER software will be used.

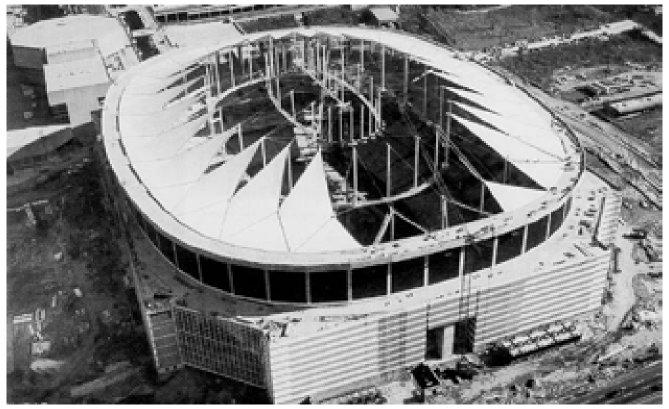


Figure 1 - The Georgia Dome in Atlanta, U.S.A. reproduced by Tibert, 1999

Matrix Analysis of Pin-joined frameworks

The matrix formulation is based on Pellegrino and Calladine theories (Pellegrino 1986). The hypotheses are:

a) members are connected by pin-joints;
b) the connectivity between nodes and members is known;
c) self-weight of members is neglected and the additional loads are applied only in the nodes;
d) buckling of the strut is not considered.

Hypotheses a) and c) let the members work only with axial forces, either in compression or tension.
When we consider a generic three-dimensional pin-jointed structure, the equilibrium equations can be written in the following form:

$$At = f \qquad (1)$$

where A is the equilibrium matrix, t the vector of internal forces and f the vector of nodal forces.
In addition, it can be proved through the virtual work principle that the compatibility equation is:

$$Atd = e \qquad (2)$$

where At is the compatibility matrix, d the vector of nodal displacements and e the vector of element elongations. Through the exploration of the balance subspaces it is possible to classify the pin-jointed framework. In fact, by defining the number of state of self-stress (s) and the number of internal mechanisms (m), we will see the situations listed in Table 1.

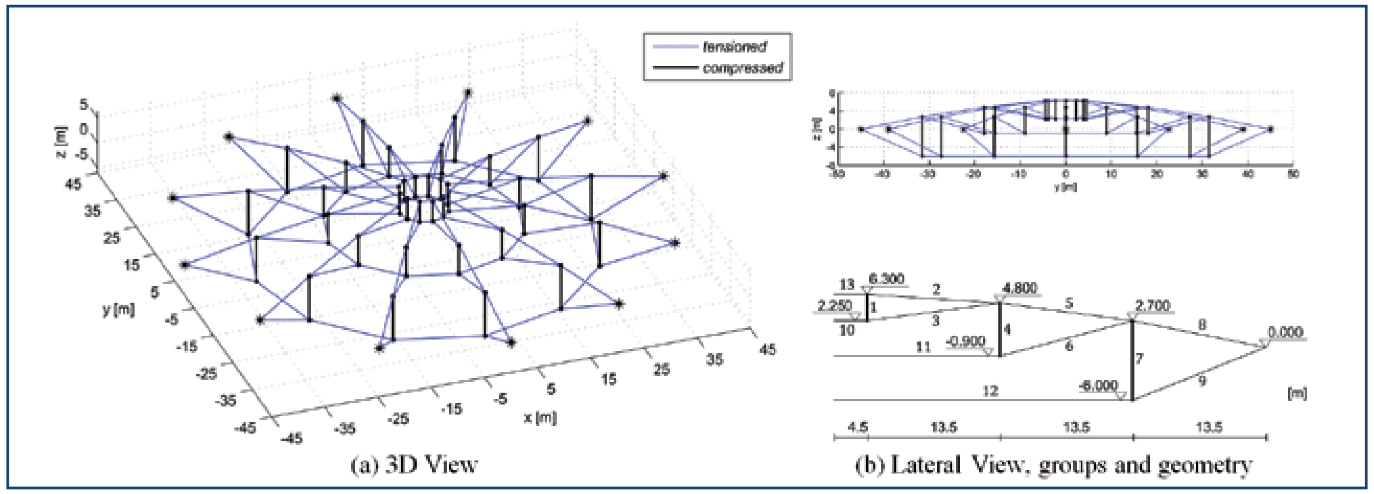


Figure 2 - Details of the Geiger dome

Type		Static and kinematic properties
I	s = 0 m = 0	Statically determinate and kinematically determinate
II	s = 0 m > 0	Statically determinate and kinematically indeterminate
III	s > 0 m = 0	Statically indeterminate and kinematically determinate
IV	s > 0 m > 0	Statically indeterminate and kinematically indeterminate

Table 1 - Classification of structural assemblies

Group no.	1	2	3	4	5	6	7	8
Prestress	-0.0433	0.3923	0.2334	-0.0963	0.6268	0.3739	-0.1961	1.0000
	9	10	11	12	13			
Prestress	0.4829	0.4431	0.6979	0.8525	0.7533			

Table 2 - State of self stress of the dome

As pointed out in “Pellegrino 1993”, all the information about the assembly can be obtained by the singular value decomposition (SVD) of the equilibrium matrix, whose details are given in “Quarteroni et al. 2008”. The state of self-stress is represented by the solutions At = 0, and the mechanism by the solution Atd = 0.

The Geiger Dome

In a Geiger Dome the ridge cables are radially oriented, and the roof is composed of wedge shaped basic units, cyclically distributed around the centre. The Geiger Dome here represented is defined by 84 nodes connected with 156 elements, as shown in fig. 2. The structure is composed of 36 struts and 120 cables. The 12 external nodes are fixed. The symmetry of the dome allows to subdivide the elements into 13 groups, as shown in fig. 2(b).
Given the connectivity and the fixed nodes, the state of self stress can be computed through the singular value decomposition of the equilibrium matrix. The results are reported in table 2. In addition, s=1 and m=61, hence the structure is statically and kinematically indeterminate. However, the self-stress state can stabilize all the internal mechanisms.
Until now, only one balance problem has been solved. In fact, since the vector reported in table 2 is a base, any coefficient ψ can be chosen, so that ψ t=0. The precise value of ψ must consider the performance of the structure under external loads and the resistance of the material. So, for practical purposes, the introduction of additional design criteria, such as structural performance in terms of rigidity and deformability, is needed. This leads us to introduce new variables, such as stress intensity and the actual section of the elements that must also match those of commercial profiles (Biondini et all 2011). The algorithm chosen here is a genetic algorithm implemented in the commercial software modeFRONTIER.

Applied loads and constraints

In addition to the prestress system, two sets of loads are considered:

a) the structural weight;
b) a live vertical load q=0.5kN/m2, uniformly distributed over the dome.

The constraints of the problem are:

1) a constraint on the maximum dome displacements:

$$d_{max} \leq \frac{l}{250} = \frac{90000}{250} = 360\ mm \qquad (3)$$

2) a constraint on cable resistance: the forces must comply with the resistance FRd provided by the manufacturer reported in Appendix A, with a safety margin $\gamma_{s,i}$ = 1,5.
3) a constraint on strut instability:

$$t_s \leq \pi^2 \frac{EI}{l_0^2} \gamma_{s,i}, \quad with \quad \gamma_{s,i} = 1.5 \qquad (4)$$

The first constraint has to be verified under loads, the second and the third have to be verified for both, the prestressing state only and for loads. So, two types of safety margins will be provided: the initial safety margins and the final safety margins.

P_{tot} [ton]	f_{max} [mm] < 360	ψ [N]	P_1	F_2	F_3	P_4	F_5	F_6	P_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}
21.98	-359.57	625638.83	7	23	7	12	16	11	20	18	14	11	16	18	34

Table 3: Optimal solution provided by modeFRONTIER

	Group no.							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
γ_{safe}	1.40	4.51	1.31	1.42	1.47	1.55	1.51	1.20
	9	*10*	*11*	*12*	*13*			
γ_{safe}	1.62	1.31	1.32	1.41	4.60			

Table 4: Initial safety margins

	Group no.							
	1	2	3	4	5	6	7	8
γ_{safe}	1.41	67.02	1.22	1.10	3.34	1.20	1.10	1.60
	9	10	11	12	13			
γ_{safe}	1.18	1.22	1.02	1.03	68.57			

Table 5 - Final safety margins

Representative design variables of the problem

The representative variables of the problem are:

- the coefficient ψ (1 variable);
- the cable sections divided into groups (10 variables);
- the strut sections divided into groups (3 variables). This means that the optimal solution is searched in a space of 14 variables. The area of the cables has to match those ones of the normalized product. The list of commercial areas considered by the genetic algorithm is reported in Appendix A. Therefore, the algorithm considers 64 different cable types. For the struts, 50 circular sections with the following defined diameter are considered.

$$\phi = 25 : 5 : 240 \text{ [mm]}$$

Results of the optimization process

The evaluation of displacements and internal forces in the elements required to assess the fitness of each individual element was made possible by Cable 3, a finite element program implemented in Fortran. The program is able to handle the load response of a general 3D pin-jointed framework considering both mechanical and geometrical non-linearities. The commercial software modeFRONTIER as dealt with the structure optimization problem were p = 40, number of individuals in the population; pc = 0.85, crossover probability; pm = 0.05, mutation probability; elitism disable. The data flow and the logic flow of the modeFRONTIER process are reported in Fig. 3. The optimal solution is shown in Table 3.

In Table 4 and 5, the initial and the final safety margin are illustrated. In fact, when dealing with cable systems, not only the final state of the structure (under all loads), but also the initial state (under prestress only) have to be verified. From the tables, we can observe that the dominant condition may be in the initial or in the final state. In fact, there are some elements that increase their force under loads (Fig. 6), while others decrease it, in accordance with the working principle of a cable system.

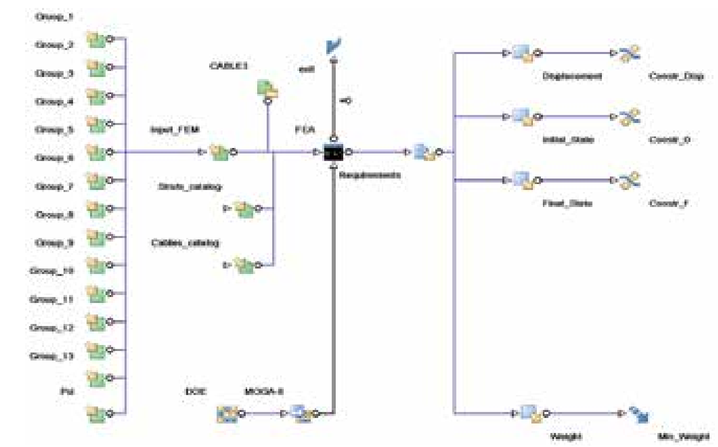


Figure 3 - Logic and data flow of the optimization process in modeFRONTIER

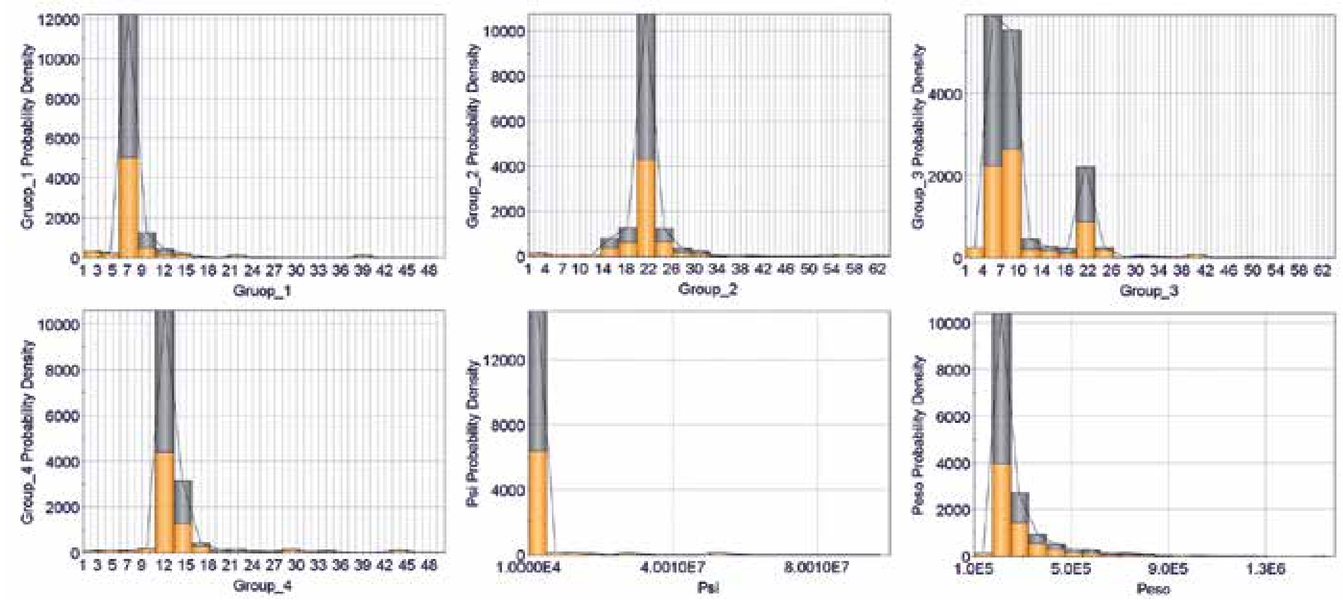


Figure 4 - Probability density function of some variables

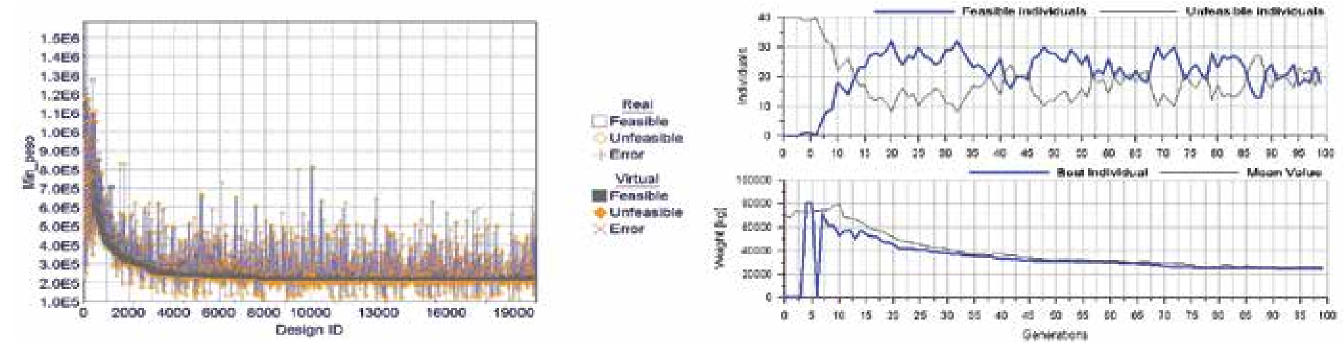


Figure 5 - Simulation statistics

For the optimal solution, the maximum deflection under loads is equal to -359.57 mm, practically coincident with the allowable maximum deflection set equal to -360 mm.

Figures 10 and 11 show respectively the deformed shape and the axial forces for the optimal solution (Straus7 2004).

Conclusion

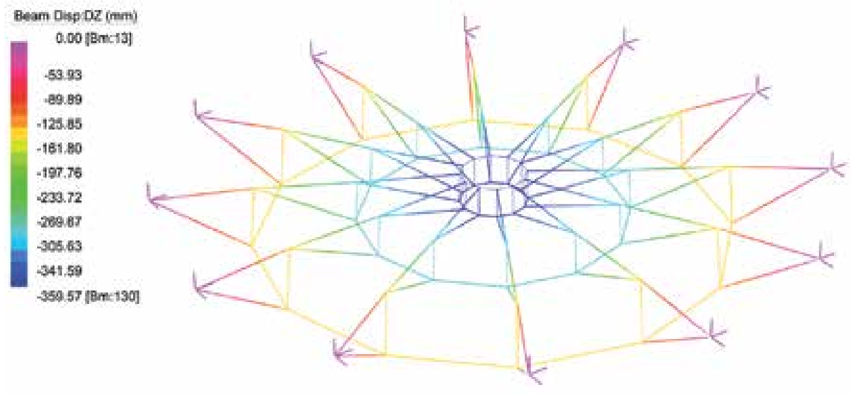
In this article, an approach to the problem of optimal designs of cable structural systems has been presented. In these systems, the solution of the initial balance problem plays a dominant role. In fact, as these structures work only through axial forces, the geometry and the pretensioning intensity applied to the elements are closely related.

Therefore, the balance configuration must be determined by specific form-finding techniques that provide both the form and the associated stress state. For practical purposes, however, this is not enough and an additional phase, that takes into account the structural performance in terms of rigidity and deformability, is needed. Experiences and intuition may not be sufficient in this second phase because the problem is affected by the geometrical non-linearities and for this reason, a feasible solution may require several trials.

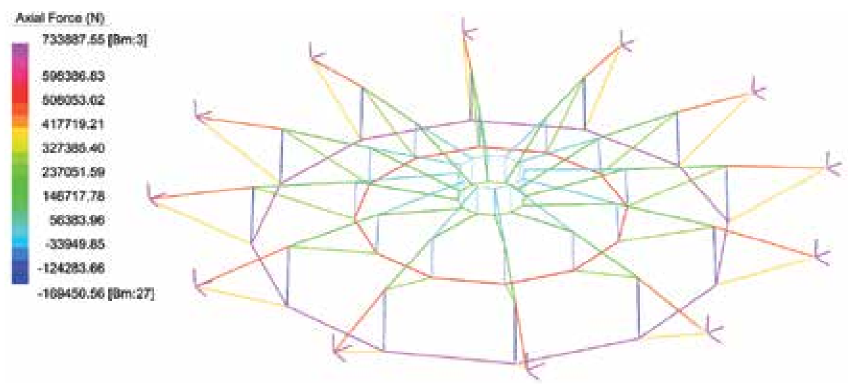
The authors have presented here a general method able to provide a design solution that is not only technologically sound, but optimal with respect to the design requirements.

In the suggested formulation, the solution for the optimization problem has been provided by the genetic algorithm included in modeFRONTIER. This algorithm has been applied to the structural optimization of a Geiger Dome.

A. Albertin, P.G. Malerba,
N. Pollini, M. Quagliaroli
Department of Structural Engineering,
Politecnico di Milano, Milan, Italy

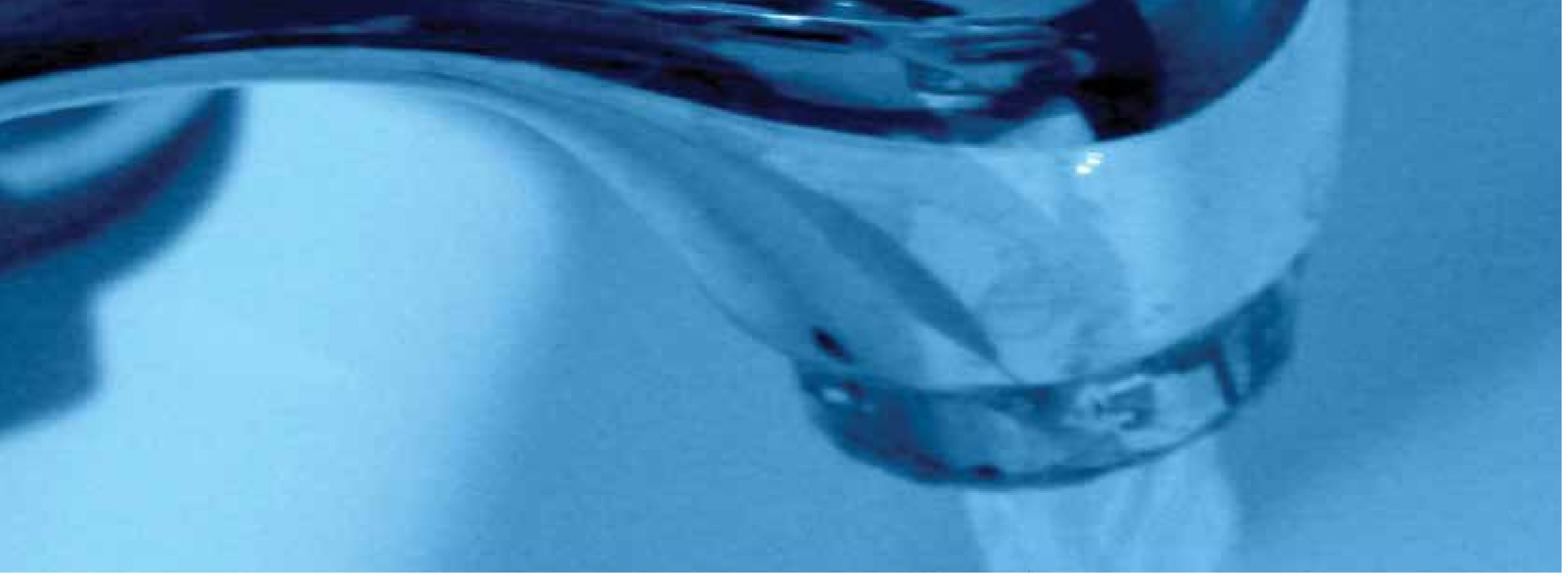


(a) Deformed configuration



(b) Final axial forces.

Figure 6 - Final control of the optimal solution with the commercial FE software Straus7



Multi-Objective Optimization of a Water Supply System

The Mono-Objective Problem

The problem considered in this article was described by Alperovits and Shamir (Alperovits E., Shamir U., 1977, "Design of optimal water distribution systems", Water Resource Research, (13)6: pp. 885-900). This a classic optimization problem that will allow us to demonstrate the power of modeFRONTIER when associated with a fast and effective software for system level simulation as Flowmaster. The considered water supply system has eight pipes arranged in two loops and is fed by gravity from a constant head reservoir as shown in Figure 1. The elevation of each delivery point s is reported in Table 1 together with the required flow and pressure. The allowed pipe diameters and the associated costs are reported in Table 3. In the simple case of a mono-objective problem in which the minimum cost is sought, it is possible to compute the optimal solution by using a FAST method associated with a genetic algorithm (MOGA-II). The optimal solution is represented by the combination of pipe diameters that minimizes the total cost of the system and is reported in Table 2. To be noted that a mono-objective optimization problem has a unique optimal solution.

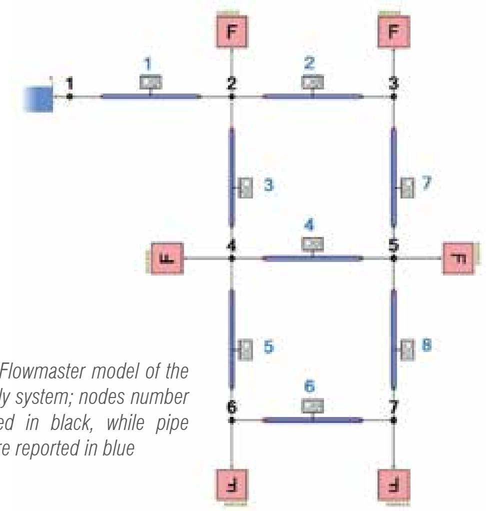


Figure 1 - Flowmaster model of the water supply system; nodes number are reported in black, while pipe numbers are reported in blue

Nodes	Demand (m3/h)	Elevation (m)	Required Pressure (m)
1	-1120	210	--
2	100	150	30
3	100	160	30
4	120	155	30
5	270	150	30
6	330	165	30
7	200	160	30

Table 1 - Required flow, elevation and required pressure at each node of the water supply system

Pipe Number	Diameter (inch)
1	20
2	10
3	16
4	1
5	14
6	10
7	10
8	1
Total Cost ($)	420 000

Table 2 - Optimal solution of the mono-objective problem

Index	Diameter (inch)	Cost ($/m)
1	1	2
2	2	5
3	3	8
4	4	11
5	6	16
6	8	23
7	10	32
8	12	50
9	14	60
10	16	90
11	18	130
12	20	170
13	22	300
14	24	550

Table 3 - Allowable diameters and associated cost

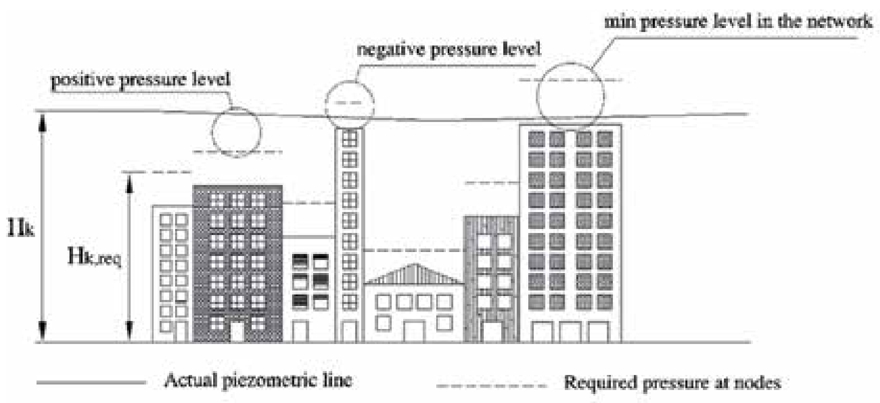


Figure 2 - Actual piezometric line (Hk) and required pressure at nodes (Hk,req) – from Nicolini (2005)

The Multi-Objective Problem

Following Nicolini (Nicolini M., 2005, "A Two-Level Evolutionary Approach to Multi-criterion Optimization of Water Supply Systems". Evolutionary Multi-Criterion Optimization, Third International Conference, EMO 2005, Guanajuato, Mexico, March 9-11, pp. 736-751), it is possible to extend the mono-objective problem to a multi-objective problem by relaxing the constraint on the required pressure. In particular, we allow the node pressure to be lower than the required pressure and search for the solutions that minimize the total system cost and maximize the minimum pressure level, i.e. the deviation of the actual piezometric level from the required pressure. A graphical representation of the second optimization target is provided in Figure 2. We also limit the region of interest for the minimum pressure level between -30m and 0m. It can be noted that the two objectives are conflicting and that this multi-objective optimization problem has an infinite number of solutions. This extension of the problem allows to exploit all the capabilities of the multi-objective optimization algorithms of modeFRONTIER.

The optimization workflow is presented in Figure 3. The input parameters are represented by eight indexes; these are manipulated by a calculator in order to compute the pipe diameters (deep blue box) and the total cost of the system. Once the total cost is computed, the minimization target can be applied (purple box). Then the pipe diameters are passed to the Flowmaster direct link (light blue box) for hydraulic computations which provides node pressure results (orange box). The pressure values are then passed to another calculator that computes the minimum pressure level. Once the pressure level is computed, the appropriate bounds and the maximization target can be applied (green box).

Sobol algorithm is used for the design of experiment (DOE), then two different genetic algorithms are used to compute the optimal designs, first the MOGA-II algorithm and afterwards the NSGA-II algorithm. This strategy allows for a good exploration of the variable space and to obtain a good definition of the Pareto frontier, i.e. the collection of the optimal solutions.

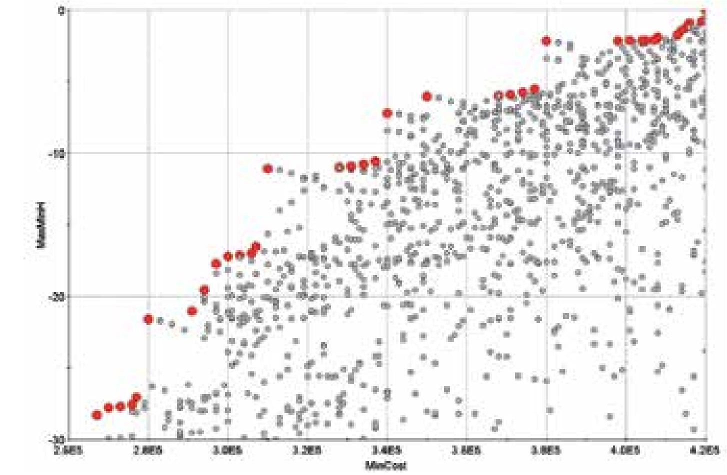


Figure 4 - Scatter plot representing the total cost and the minimum pressure level of each design; optimal designs are highlighted in red

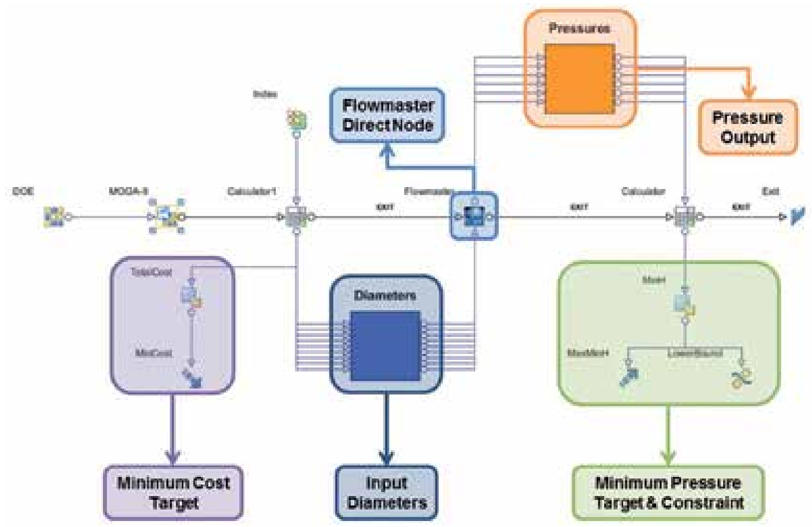


Figure 3 - modeFRONTIER optimization workflow

In Figure 4 a scatter plot representing the total cost and the minimum pressure level of each design is presented; the optimal designs are represented by red bubbles. Among these, the optimal solution of the mono-objective problem can be recognized in the upper-right corner; the total cost of this solution is 420 000$ and its pressure level is 0, i.e. the actual piezometric level equals the required pressure head. On the other hand it can be noted that if a deviation from the required pressure head is accepted, then cheaper designs can be implemented. All these designs are optimal in the sense that there is no other design capable to improve both targets at the same time. In Figure 5 a parallel coordinate plot is presented in which only optimal designs are reported. The left coordinate axis represents the total cost of each optimal design while the right coordinate axis represents its pressure level. This plot is very helpful for decision making because it clearly shows the relations between different targets. For example, a system that costs 377 000$ will produce a deviation from the required pressure head of 5.53m. A little increase on the cost will produce a large reduction of the deviation, indeed a system that cost 380 000$ (only 3 000$ more than the previous one) will produce a deviation of 2.19 m. On the other hand a large increase in the cost from this solution will not produce an adequate reduction of the deviation, indeed a system that costs 398 000$ (18 000 $ more than the previous one) will produce a deviation of 2.17 m.

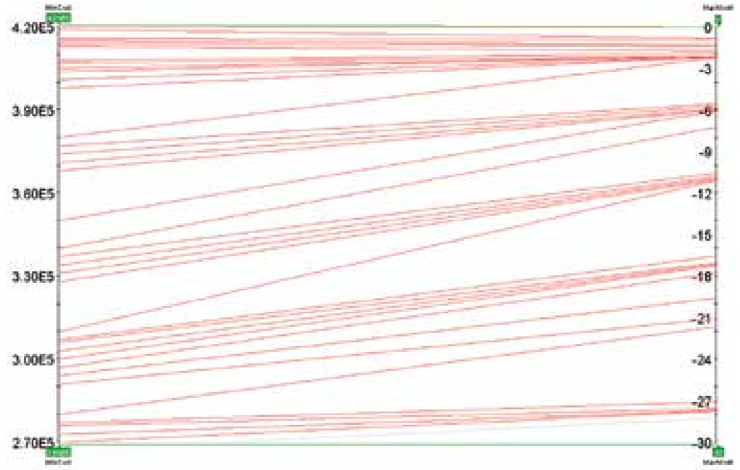


Figure 5 - Parallel coordinate chart representing the total cost and the minimum pressure level of each design; only optimal designs are shown

Conclusions

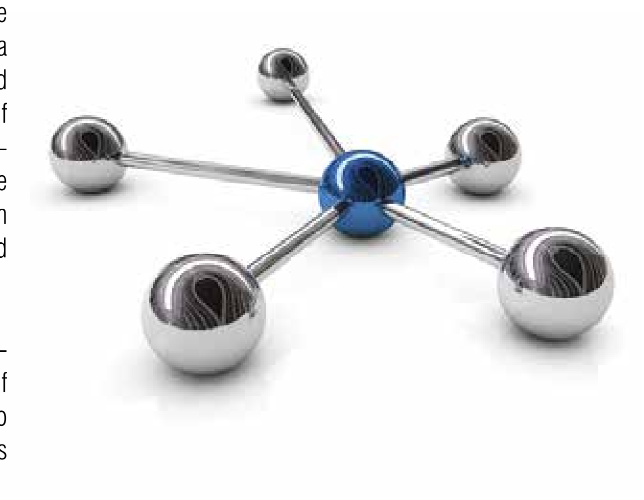
The simple water supply system considered in this work allowed to investigate all the difficulties related to the optimization problem and to exploit all the capabilities and opportunities offered by a coupled use of simulation tools such as Flowmaster (the hydraulic simulation tool) and modeFRONTIER (the optimization tool). In particular, a mono-objective optimization problem was extended to a multi-objective optimization problem where two conflicting targets were optimized, namely the total system cost and the deviation between the actual pressure head and the required pressure head. This multi-objective problem has an infinite number of solutions; all the optimal solutions lays on the Pareto frontier. The use of two genetic algorithms provided a good exploration of the variable space and a good definition of the optimal configurations. Finally, the use of adequate charts allowed to clearly visualize all the optimal solutions and to understand the relation between the two different targets. These plot can be very helpful in the decision making process because they are capable to highlight the improvements that can be achieved by changing inputs or by relaxing some requests.

This example showed that a simple mono-objective optimization problem can be extended to a more complex multi-objective optimization problem opening a wide range of possibilities. In the same way, this multi-objective optimization approach can be extended to a more complex real-life water supply system… but optimization is not limited to water system only; indeed it can be applied to any system, regardless of its complexity. The use of multi-objective optimization during system design process allows for great enhancements in system performances as well as large cost reductions.

Alberto Deponti, Silvia Poles - EnginSoft

The integration between Flowmaster and modeFRONTIER

One of modeFRONTIER's many direct integration nodes is for Flowmaster. This allows Flowmaster users around the world to exploit the most complete optimization software tool available on the market. The integration provides a consistent environment for simulating and optimizing fluid mechanics and pipe flow in simple-to-complex systems. Components and node parameters of thermos-fluid systems analyzed with Flowmaster are captured thanks to an easy-to-use Parameter selector wizard within modeFRONTIER and the user can define the input and output variables for the automatic workflow creation. Simulation data can also be set from within modeFRONTIER for both compressible and incompressible flows.



The combined use of Flowmaster and modeFRONTIER allows for the multi-objective optimisation of complex fluid systems. Moreover, the velocity of Flowmaster simulation together with the power of modeFRONTIER allow to evaluate a great number of different designs and to find the optimal solutions quickly and efficiently.

Handling the Complexity of Mechatronic System Design

How multi-disciplinary design optimization helps resolve major challenges in the automation industry

Optimization-Based Development of Ultra High Performance Twin Robot Xbar Press Tending Robot System

Two design projects highlight how ABB Group leverages optimization-based development to handle the complexity that automation and control systems entail and to maximize mechatronic product performance, meet reliability demands and ease overall environmental impact.

ABB Group, a global leader in power and automation technologies, covers almost every segment of the power generation and industrial process control market with its products and systems. With $1.4 billion in annual investments, the 8,500 engineers and scientists at ABB Research & Development are committed to meeting the automation industry's ever-increasing demand for reducing energy consumption and improving reliability and performance.

The design projects illustrated here highlight how ABB Group leverages optimization-based development to handle the complexity that electronic and software components entail. Looking at system interdependencies from the earliest concept phase is crucial for an effective strategy that aims at maximizing product performance, meeting reliability demands and easing the environmental impact of their products.

THE INDUSTRY CHALLENGE

Industrial robots are sophisticated systems incorporating hardware and – increasingly – software components. Subsystem design (gearboxes, motors, sensors and brakes) and the interactions between elements such as machine interfaces, safety integrations, field buses, PCBAs, power supplies and drive modules must be carefully planned to assure the best possible performance. Over the years, cost pressures have made robots a commodity in terms of physical specifications. Among the many design challenges, the need for lighter components has resulted in reduced stiffness, making the control problem more complex. Furthermore, many third-party interfaces require integration and products that must comply to software, electrical and mechanical quality standards.

ABB EXPERIENCE

In the case of the Twin Robot Xbar Press Tending Robot System, one of ABB's flagship robots, engineers considered 18 design variables

(representing the gear torque, motor torque and motor speed) and managed objectives and constraints in modeFRONTIER, achieving a 12% energy saving, solely by varying the software components. "We optimized this robot 'manually' for 30 years and it is one of the most used. With modeFRONTIER we were able to identify a new design – requiring no implementation costs – bringing 12% of energy savings without compromising performance by changing only the software configuration. Obviously, this is something that can't be done by hand – you need an optimization software to do it." says Dr. Wappling, Global R&D Manager at ABB.

> With modeFRONTIER we obtained a 12% energy saving, without compromising performance. Obviously, this is something that can't be done by hand
>
> Octavian Craciun
> Senior Scientist at ABB

modeFRONTIER ADVANTAGES

"The ability to manage mechatronics is becoming increasingly important as simulation encompasses more and more systems and not just components: the impact of the mechanics, electronics and software all need to be accounted for." continues Wappling. ESTECO technology keeps pace with evolving R&D needs and provides designers with a flexible environment that handles each delicate step of complex system analysis and enhancement. As seen in the example of the robot, inserting virtual control models in the simulation framework enables designers to apply the optimization approach, calibrate the software and identify zero-cost solutions.

Octavian Craciun
Senior Scientist at ABB

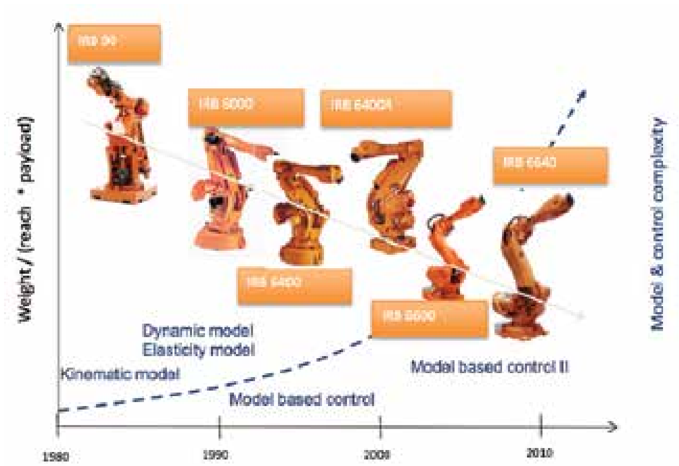


Figure 1 - The evolving complexity of mechatronics design

Multi-objective Optimization of a Medium Voltage Recloser

THE CHALLENGE

Medium voltage reclosers now represent an important grid protection device that connects different grid sources, increase the network/grid reliability and make the implementation of self-healing and auto reconfiguration schemes for overhead lines possible. With a high level of renewable energy penetration, medium voltage networks are becoming bidirectional. Therefore, the associated switching devices must ensure the protection of newer types of power systems as well as new types of loads. The optimal design of medium voltage reclosers is therefore important in order to enable excellent switching capabilities.

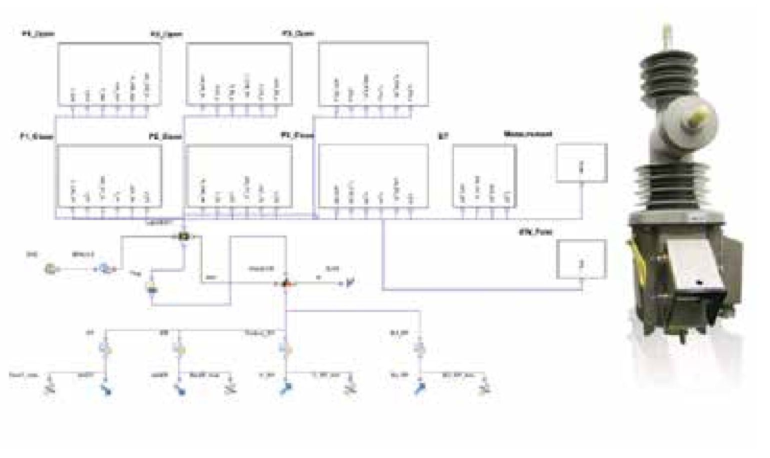


Figure 2 - modeFRONTIER workflow piloting the Hardware-In-the-Loop (HIL) process

The switching capabilities of medium voltage recloser can be influenced by various parameters such as actuation energy responsible for opening and closing the device. Therefore, to maximize the lifetime of the recloser, it is essential to establish an optimized control especially related to the actuation energy. The goal of the multi-objective optimization is to identify an optimal actuation energy control strategy for the closing and opening operations.

THE SOLUTION

ABB R&D Teams built a two-step optimization framework that incorporates the energy efficiency constraints by working initially on the electromagnetic actuator and directly optimizing the Finite Elements Model (FEM). The numerical simulation step was then completed with physical calibration via a Hardware-in-the-Loop (HIL) optimization process, ensuring that the whole system reaches the desired performance.

During the first iterations, modeFRONTIER helped improve the FEM model by identifying the best configuration possible for the electromagnetic system, while satisfying the constraint imposed by the design boundary conditions. The parameterized FEM model created with COMSOL Multiphysics was connected to Matlab LiveLink so as to pilot all design changes automatically and control both models in sequence, leveraging the direct integration node for Matlab in modeFRONTIER. In the second step, the R&D Teams opted for the in-depth analysis of the system where modeFRONTIER was coupled both with the simulation model and with the hardware to further enhance the switching properties. The HIL framework enabled an investigation environment for the whole recloser system.

Thanks to this approach, optimization can be applied to the control scheme implemented with CompactRIO/LabVIEW: after running one full closing-opening operation, data is transferred to Matlab for post processing and reinserted in the loop for the next runs. Since reducing overtravel and backtravel is extremely important for the product lifetime, with modeFRONTIER piloting the HIL system (1,500 runs with a DOE featuring selected parameters from the first optimization step), R&D Scientists pinpointed a new control scheme that enables significant extension of the product lifetime. "The identified control scheme enables up to 50% reduction of the overtravel and backtravel, enabling a remarkable improvement in terms of lifetime", says Octavian Craciun Senior Scientist at ABB.

> The optimal identified control scheme reduced parameters by 50%, enabling a remarkable improvement in terms of lifetime
>
> Daniel Wappling
> Global R&D Manager at ABB

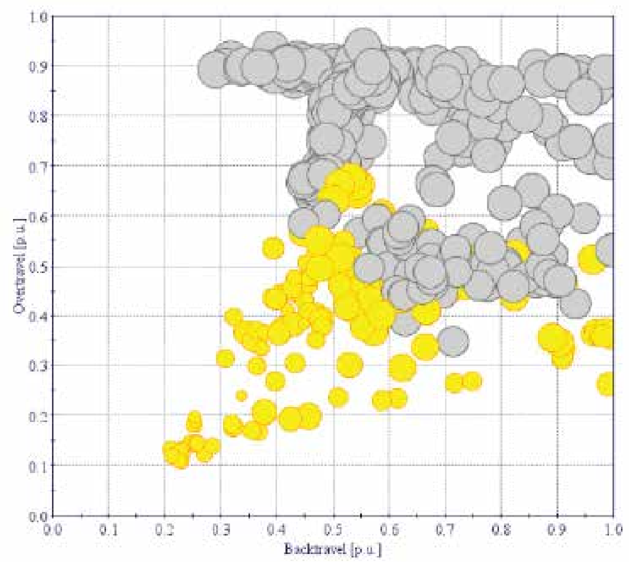
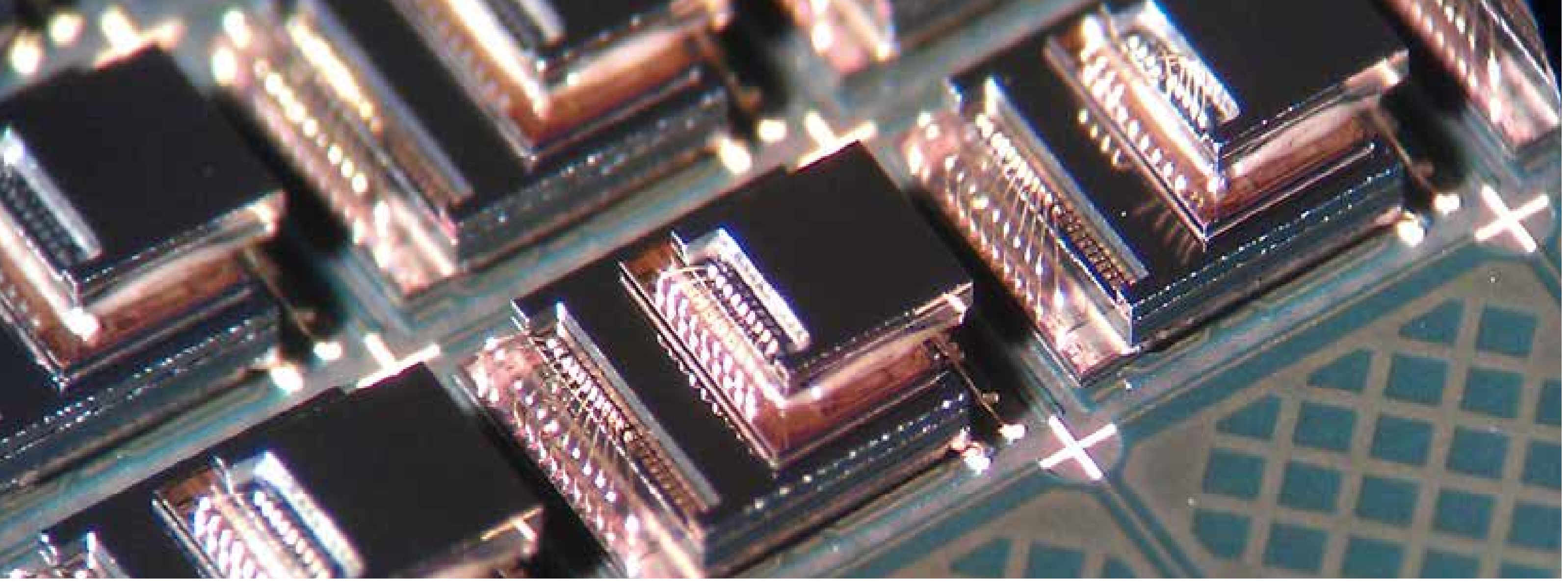


Figure 3 - Optimal control scheme for the travel curve maximizing recloser lifetime

Daniel Wappling
Global R&D Manager at ABB



Multi-Objective Optimization of a Ball Grid Array of a capacitive MEMS

Capacitive MEMS accelerometers may be directly soldered to the printed circuit board by an array of solder balls. Differences in the thermal expansion coefficients of the pertinent materials cause deformations of the accelerometer under temperature change. This may cause a relative movement of the sensing masses with respect to the sensing electrodes, resulting in a change in capacitance and a false acceleration output. A multi-objective optimization was used to find the best location of the solder balls which minimized the measurement error under varying temperature and, at the same time, maximized the expected service life due to fatigue of the solder balls. While the achieved improvement in service life was moderate, an order of magnitude improvement was achieved for the predicted measurement error.

1. Introduction

VTI Technologies Oy develops and manufactures micro electro mechanical systems (MEMS) and the main products are capacitive low-g accelerometers which for instance are used in automotive electronic stability control (ESC) systems. An accelerometer is attached to the printed circuit board (PCB) by an array of solder balls. The attachment type is referred to as a ball grid array (BGA) due to the shape and layout of the solder balls (Figure 1). The measurement principle for a low-g accelerometer is outlined in Figure 2. A mass is attached to an anchor via a spring, and under acceleration the mass which holds the sensing electrodes moves with respect to the static electrodes. The movement changes the gap and thus the capacitance which is then measured. The final product which is soldered to the PCB includes multiple materials, each with a different thermal expansion coefficient. Unfortunately this may cause the sensing elements to move as change and send out a false acceleration output, referred to as an offset error.

Accelerometers are normally exposed to small vibrations which may cause fatigue and failure of the electrical connection between the accelerometer and the PCB. Both the offset error and the fatigue life are affected by the layout of the BGA and the objective of the study is therefore to minimize the offset error and, at the same time, maximize the expected service life.

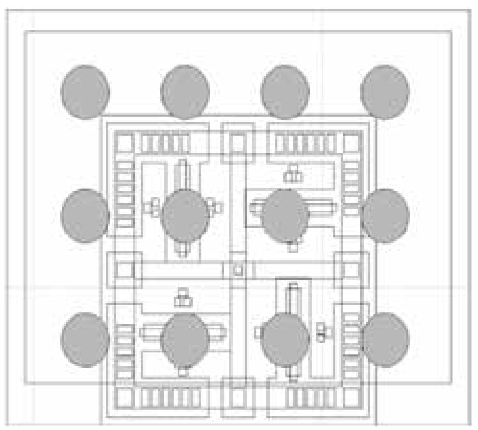


Figure 1 - The baseline design of the ball grid array is evenly spread over the available surface. The MEMS structure may be seen behind the gray solder balls

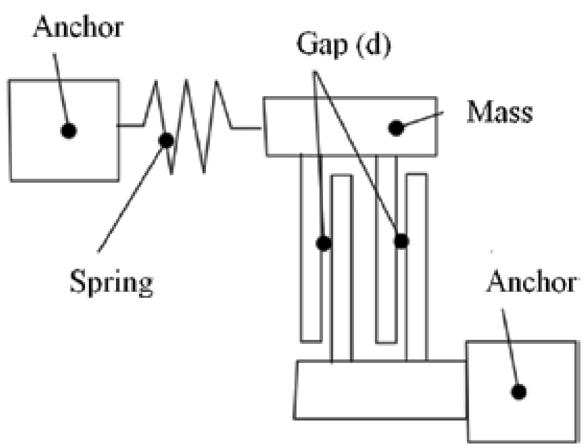


Figure 2 - A low-g accelerometer measures the change in capacitance with varying gap size. The gap, typically 1.5 to 3 μm, changes when acceleration forces move the mass

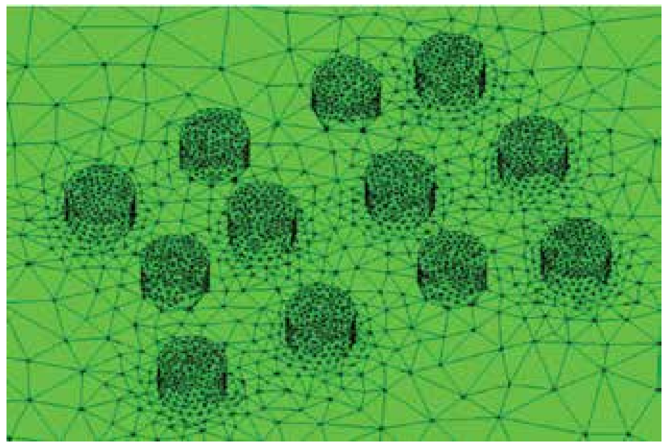


Figure 3 - The solder balls, seen on top of the PCB, have a refined mesh

2. The numerical model

In order to keep the model size reasonable, the active sensor elements were not included in the FEM model. We assume the movement of the anchors can be directly mapped to the offset error, i.e. the larger the movement, the larger the offset error as a function of temperature.

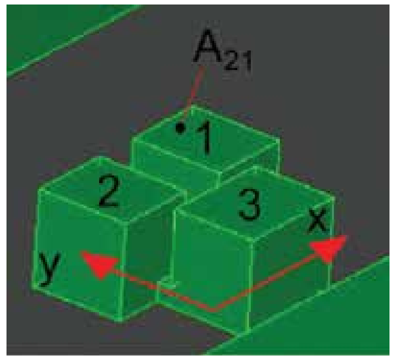


Figure 5 - Anchors and their numbering within one of the sensors measuring in the y-direction

Mesh controls were employed to ensure dense mesh in critical parts of the model and to achieve a consistent mesh between different geometries. Ten noded tetrahedral elements were used in the linear model and typical model size was 400000 elements or 1.65 million degrees of freedom. Plasticity and creep of the solder was omitted and two load cases with different temperature were used, +85°C and –40°C.

Figure 3 displays a part of the meshed model, the solder balls on the PCB.w

3. Multi-objective optimization

The general multi-objective optimization software modeFRONTIER was used to automate the design evaluations and steer the process towards its optimum. The generalized process has been outlined in Figure 4 and consists of setting input parameters, running the simulation, reading the results and deciding which design to evaluate next. The loop is then repeated until the optimum has been found or, more commonly, good enough results are obtained and resources are needed better elsewhere.

3.1 What to measure

An optimization task always starts with the definition of the objectives and how to measure them. The selected result should in a single number capture how well the design performs with respect to the objective. In this case the value function F^{tot} was a measure of the relative movement of the anchors of the sensing and static electrodes:

$$F_{tot} = \left|F\left(D_{1j}\right) + F(D_{3j})\right| + \left|F\left(D_{2j}\right) + F(D_{4j})\right| (1)$$

where the average displacement of the top surface of an anchor is defined as

$$D_{ij} = \frac{1}{A_{ij}} \int_{A_{ij}} u_{ij}(x,y)dydx$$

The sensor was identified through i=1,2,3,4 and j=1,…,6 identifies the anchor within the sensor, see figure 5. Sensors i=1,3 measure in the x-direction and sensors i=2,4 in the y-direction. u is the x-displacement for i=1,3 and the y-displacement for i=2,4.

To maximize the service life, one aims to minimize the solder fatigue through minimizing the peak stress in the solder balls.

3.2 Parameterization of the BGA layout

It was desirable to investigate a large design space which included fundamentally different designs compared to the baseline, see figure 6. For that reason the parameterization had to be very general, allowing each solder ball to move freely over most of the surface, see figure 7.

In order to take manufacturing constraints into account, the minimum allowed distance between center to center of two solder balls was increased from 330 μm, respecting only the solder balls, to 500 μm.

3.3 Process automation

Each design candidate was evaluated in an automatic process, including import of CAD geometry and moving each solder ball to the specified location. The design was then meshed, solved and the offset error, as well as the stresses, was extracted. Based on the log files, a command file in Matlab format was assembled which carried out the process above. The command file included the move command of each solder ball as well as a set of custom postprocessing commands. Besides saving the specified results to an ascii file, several plots of interesting results were saved for continuous monitoring.

In order to capture designs where solder balls were located too close, a collision detection check was implemented directly in modeFRONTIER. As can be seen in figure 8, each design candidate is first checked for collisions. Only designs with zero collisions are passed on to the solver for evaluation.

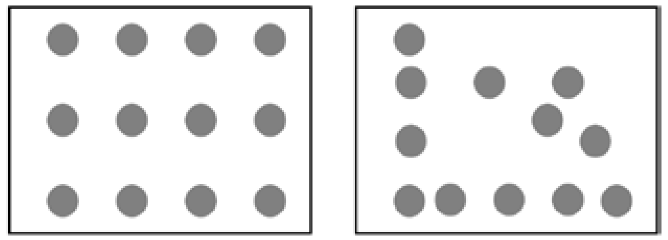


Figure 6 -- t was desirable to try out very different BGA layouts such as the example on the right, compared to the baseline design to the left

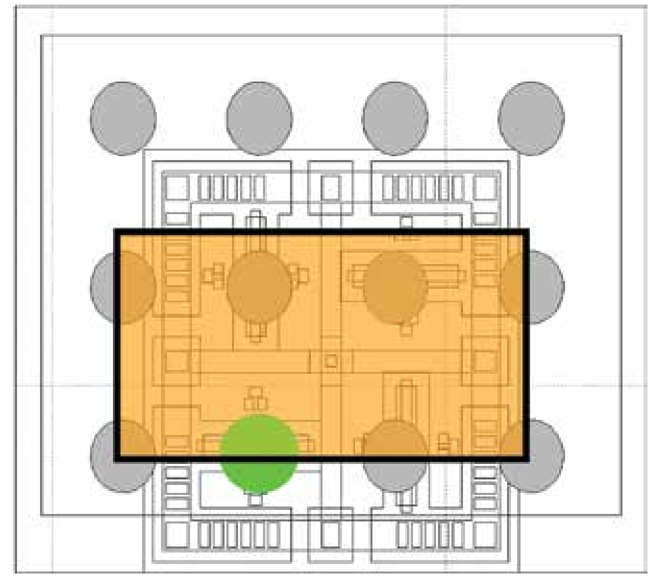


Figure 7 - In order to realize probably every possible design configuration, the parameter ranges of each solder ball had to be generous. The orange rectangle shows the parameter space of the green solder ball

The optimization was run on a 64-bit Linux system and the solution time for a design evaluation varied from 9 to 15 minutes.

4. Optimization strategy

In order to allow BGA design layouts which were very different from the baseline design, the range of each input parameter had to be wide. It was therefore not possible to avoid collisions. As the collision check stops impossible designs from being evaluated, the learning process of the optimization algorithm is slowed down. A good choice for this type of situation is the Multi-Objective Genetic Algorithm (MOGA-II), one of the most popular algorithms available in modeFRONTIER. By using a population of designs, it mimics the genetic mechanisms found in nature to search for the best designs. Here, an initial population of about 50 designs would be suitable.

4.1 Creating the initial population

The initial population may be created by setting up a large Design of Experiments (DoE), running the collision test and then selecting 50 well separated designs from those who pass. Unfortunately, a Sobol space filler DoE of 256000 designs was executed in 1.5 hours without finding a single feasible design. In this 24 dimensional input parameter space, collisions between the solder balls are obviously common.

In the second attempt, 6 interesting and different BGA layouts were designed manually. Unfortunately, only the baseline design solved without errors. A later investigation revealed that the root cause was the mesh control settings but at this stage, the model was not changed.

The third attempt used the baseline design as a starting point for the Multi-Objective Game Theory (MOGT) algorithm. Despite being a pretty efficient and simple algorithm, MOGT evaluated 168 designs in 5 hours before it was manually stopped. Out of the 168, 140 designs failed to evaluate, mainly due to colliding solder balls, but some 5 percent due to geometry, meshing and solver errors.

Figure 9 shows the two conflicting goals where the utopia point, located in the lower left corner, implies a vanishing offset error at the lowest peak stress possible. The best designs with respect to the conflicting objectives are called the Pareto set (marked by green rings), and are located at the Pareto front (orange line). As a welcome side effect in our search for a suitable initial population for MOGA, we found a design which had 2% lower stress and 74% lower offset error than the baseline design.

4.2 Multi-objective optimization

Good initial designs are one of the most efficient ways to speed up the optimization process for obvious reasons. Another is to reduce the size of the design space which is being searched. In this case, the reduction of possible combinations was not the main reason. Instead, smaller parameter ranges decreased the risk of collisions and hence increased the possibility for the algorithm to learn.

Using the parallel coordinates chart, see figure 10, the variation between the current Pareto designs was evaluated for each input parameter. In order not to limit the performance of the best

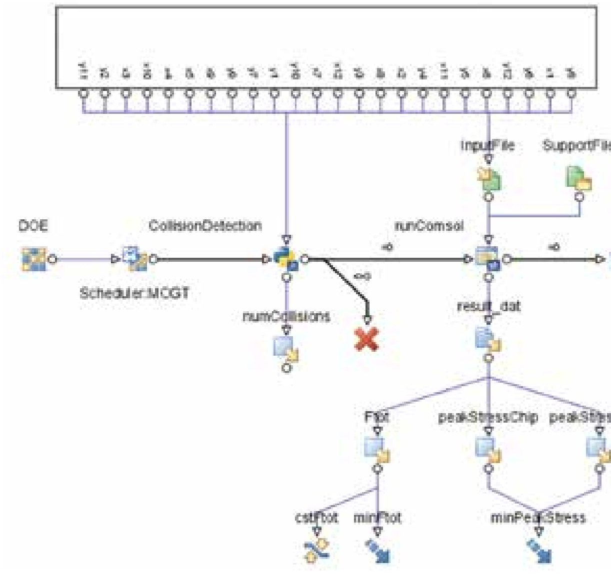


Figure 8 - The optimization logic is visualized by the modeFRONTIER workflow. At the top there are 24 input variables and under the bold process line we find extraction of results and specification of constraints and objectives. Each design is checked for collisions and only zero-collision designs are passed on to the solver

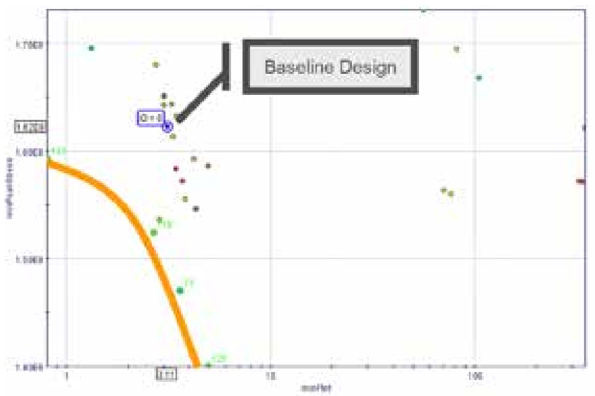


Figure 9 - Starting from the baseline design, the Multi-Objective Game Theory algorithm was able to find significantly improved designs in 5 hours. The orange line marks the Pareto front between the conflicting objectives: minimization of offset error (x-axis) and minimization of peak stress (y-axis)

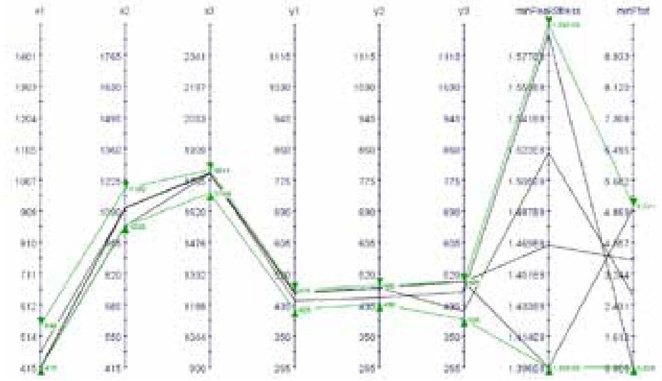


Figure 10 - The parallel coordinates chart shows both objectives and the input parameters in the same diagram for the 4 Pareto designs. Compared to the specified input ranges, showed by the full height of the axes, the Pareto designs are concentrated to a narrow zone. Based on this, the parameter ranges were reduced before starting the MOGA optimization

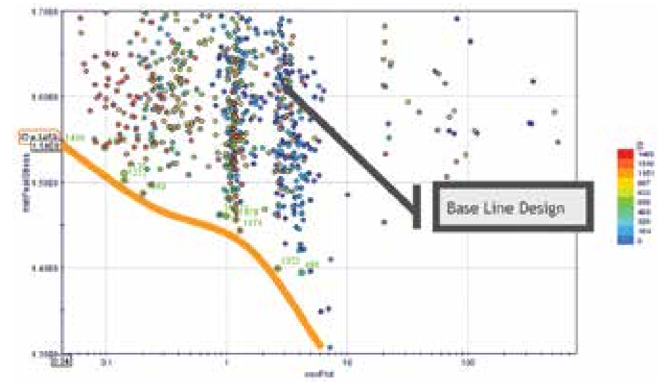


Figure 11 - The multi-objective optimization aims to reveal the Pareto front, marked by the orange line. The marked designs in the lower left corner represent the best trade-off designs between offset error and service life. Note the two zones with accumulation of designs which indicate some issue with the analysis

solutions, a margin of approximately the same size as the variation was added when each input parameter got a new reduced range.

It was decided not to follow the recommended size of the initial population but rather use a significantly smaller set. The main reason for this was the inability to create an initial population with non-colliding BGA layouts from all regions of the input design space. The 10 best designs of the MOGT optimization were therefore chosen, trusting that MOGA would make a steady evolution towards better designs while avoiding colliding BGA layouts.

The strategy worked and MOGA evaluates 990 new designs of which 759 completed successfully in 5 days. As can be seen in figure 11, the Pareto front has been stretched out and filled with more designs. While the stress levels were moderately improved compared to the first optimization, the offset error was now close to being eliminated.

5. Results

An extended Pareto front was found which showed improvements in both objectives compared to the baseline design. As always in multi-objective optimization, there is no single best design but rather a set of trade-off designs between the conflicting objectives. The best design with respect to peak stress had 14% lower stress and 15% lower offset error. The best design with respect to offset error had 5% lower stress and 99% lower offset error compared to the baseline design.

Figure 12 shows the shear stress in two planes, close to the PCB and close to the MEMS chip. Close to the chip, the stresses appear to concentrate on the balls in the corners of the grid.

The achieved reduction in the offset error by two decades is a significant improvement to the temperature stability in comparison with the base line design.

Conclusions

The presented work has showed that the offset error may be close to eliminated. In order to increase the accuracy of the model a capacitance calculation should be included. This enables minimization of computed offset error in acceleration units instead of the current anchor displacements.

Manufacturability may also be studied by analysing the sensitivity of the results due to small changes in the location of the solder balls. In other words, we are looking for a robust global optimum.

An order of magnitude improvement in measurement error was achieved which may validate the sensor to a wider range of applications which are demanding with respect to specified offset error.

H. Strandberg - EnginSoft Nordic
T. Makkonen2, J. Leinvuo - VTI Technologies Oy

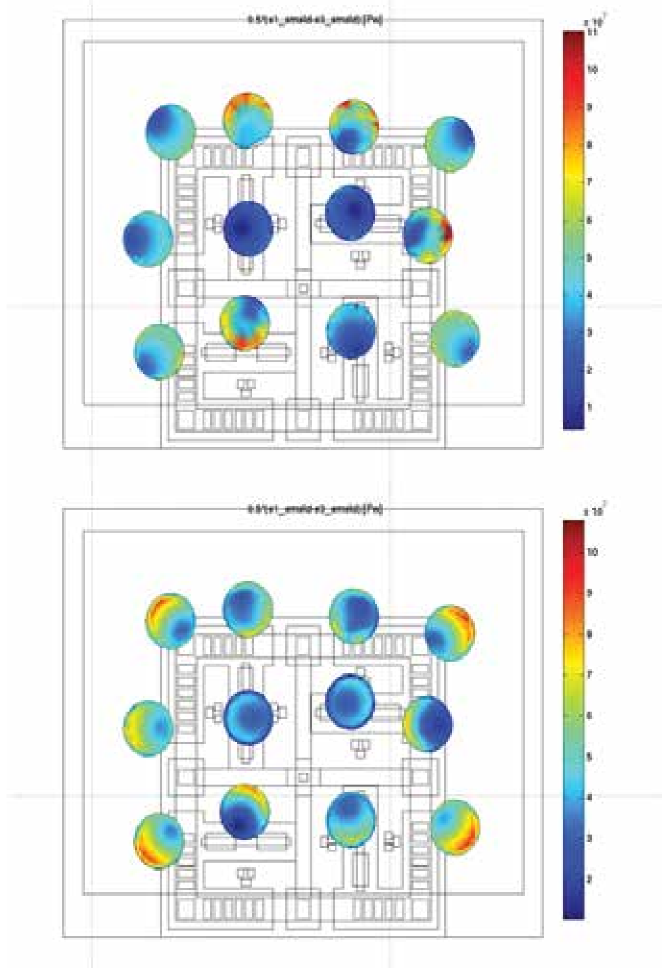


Figure 12 - Shear stress in the plane close to the PCB (upper) and the MEMS chip (lower)

Multi-objective Optimization with modeFRONTIER Applied to Systems Biology

Systems biology, the art of simulating biological processes in a computerized environment, is of growing interest due to numerous applications for e.g. the pharmaceutical industry. In this article modeFRONTIER was used to automate and optimize an analysis model written in MathModelica, a modelling and simulation software based on Modelica.

Insulin signalling

When the body detects glucose in the blood, e.g. after digesting a meal, the hormone insulin is released to signal various cells, such as fat cells, to absorb the glucose from the blood to prevent the blood sugar levels from becoming toxic. In this study, a MathModelica model of this process, shown in figure 2, was run through modeFRONTIER for optimization and analysis.

In the laboratory measurement process, human fat cells are exposed to insulin and the levels of certain indicator proteins are measured as the response.

The goal of the optimization process was not to identify a single solution to the model-fitting problem, but rather multiple solutions with acceptably small errors but at the same time with as widely varying parameters as possible. By identifying model properties shared among these different solutions, future experiments could be planned to further improve the model.

Optimization and clustering analysis

A significant number (tens of thousands) of MathModelica simulations were run through modeFRONTIER (see figure 3 for the workflow setup) and several thousand solutions with an acceptably small error between measurement data and model predictions were identified. Since the goal was to identify different sets of solutions, a Partitive Clustering Analysis was carried out on the data.

In clustering, the goal is to identify groups (clusters) of similar solutions. A cluster is well-defined if the mathematical distances between its centroid (centre-point) and those of its neighbouring clusters are large compared to the distances between the points in the cluster and its centroid. The Davies-Bouldin index, best described as the ratio of intra-cluster to inter-cluster distances, is an indicator of the quality of the clustering. The lower the index, the better separated the clusters are from each other.

Figures 4 and 5 show the results of the clustering. In figure 4, all designs have been colour-coded according to which cluster they have been assigned. In figure 5, the centroids for each cluster are shown. The difference between parameters v1ak1 (first on the left) and v1rk1 (one step to the right of the middle) is illustrated in this chart: for v1ak1, all the clusters have similar values, whereas for v1rk1, different clusters have different values. The conclusion to be drawn here is for any good fit of the model, v1ak1 will have the same value but we can find different values for v1rk1 which all generate good results. This matches the biological behaviour where different people have different body chemistries, yet still manage not to die from blood sugar poisoning.

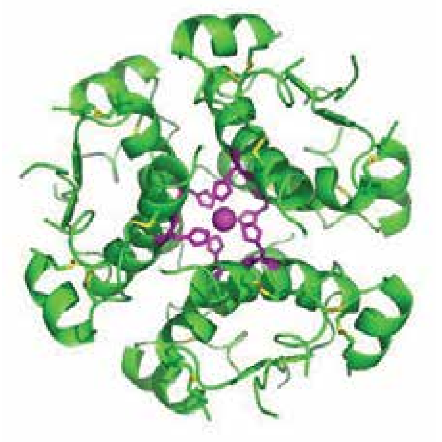


Figure 1 - Six insulin molecules assembled in a hexamer, the form in which the hormone is stored in the human body. Source: Wikimedia

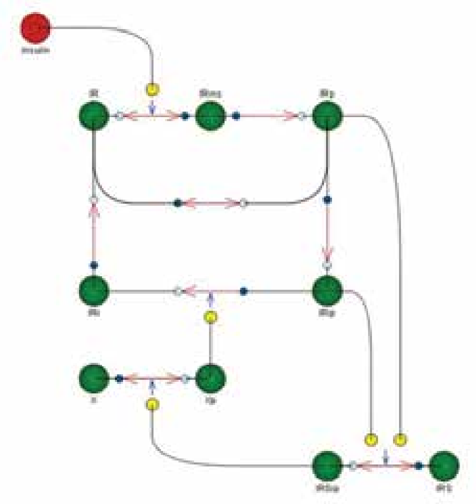


Figure 2 - The MathModelica model

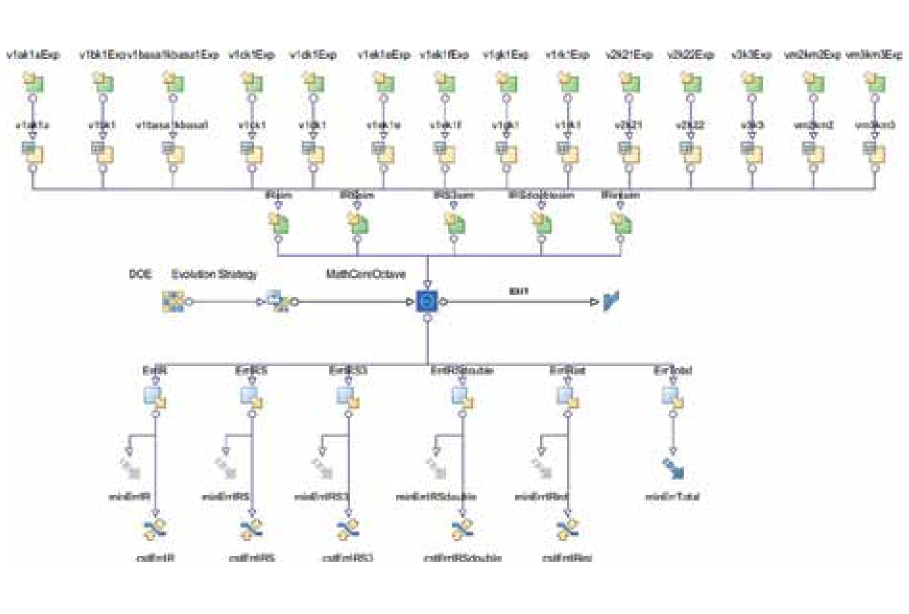


Figure 3 - The modeFRONTIER workflow

Conclusions

By using Partitive Clustering Analysis, one of the tools available in modeFRONTIER for Multivariate Analysis (MVA), information regarding complex system behaviour was identified that could not readily be understood using the normal tools available in the Design Space such as Scatter Charts and Parallel Charts.

The data extracted from the analysis regarding the different solution clusters could then form a baseline for determining future experiments and measurements.

Adam Thorp - EnginSoft Nordic

Thanks to Elin Nyman at Linköping University for help with modelling and simulations.

For an animated explanation of insulin signalling, please watch the movie "Insulin Signaling (Signal Pathways)" at: http://www.youtube.com/watch?v=FkkK5ITmBYQ

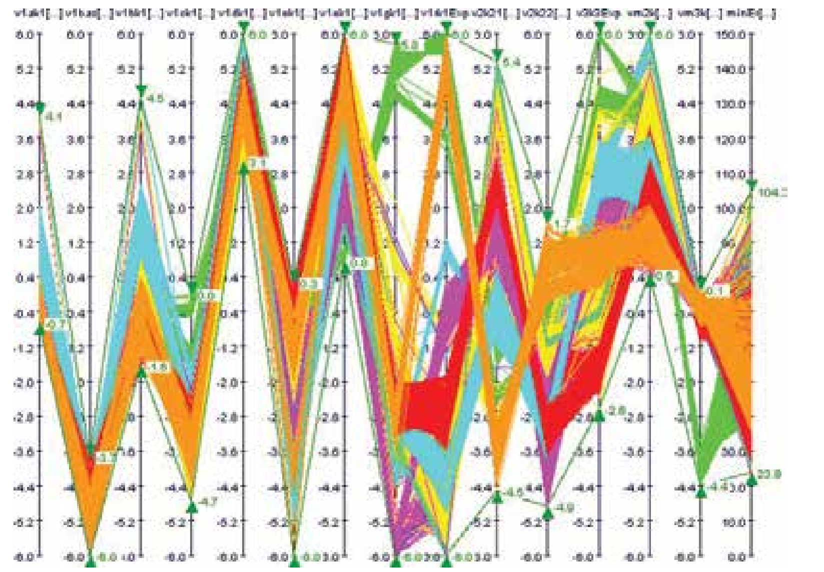


Figure 4 - The Partitive Clustering Analysis identified 8 separate clusters

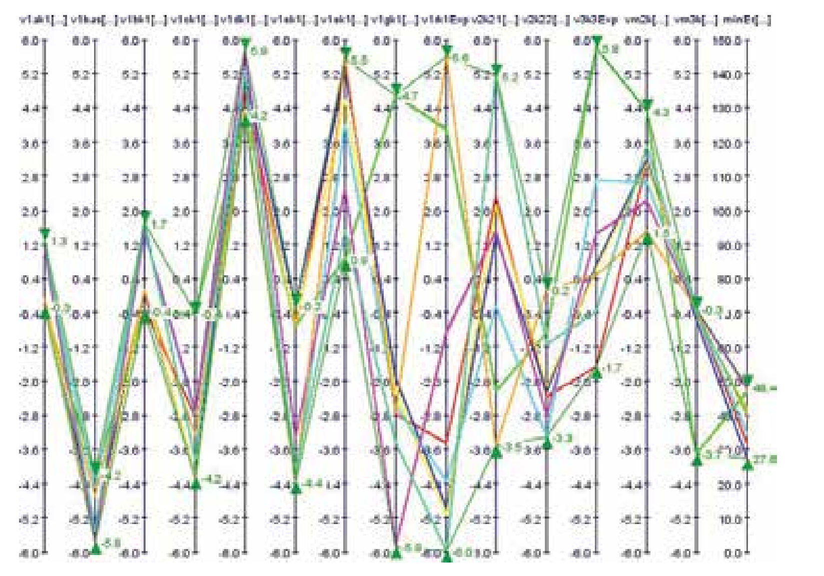


Figure 5 - A plot of the cluster centroids highlights the differing behaviours for the parameters

Optimization of a low noise hydraulic piston pump

Minimize the noise emission while maintaining the same level of performance in a pump

The use of compact axial piston pumps of the swashplate type as input power source for modern hydraulic circuitry is common, nowadays, on both fixed and mobile applications. Beside the constant focus on pump efficiency and performance improvements, within the last few years significant attention has grown on pump noise reduction, especially for electrically powered systems as for example injection molding machines.
The objective of this project was to take a standard pump (MVP60, Figure 1) with a maximum displacement of about 84 cc/rev and to minimize the noise emission, while maintaining same levels of performance.

New technology

It is well known that pump noise mainly comes from pressure fluctuations in the hydraulic circuit (fluid-borne noise) and large alternating forces inside the pump, both of which leading to the structure vibration (structure-borne noise) and the sound propagation on surroundings (air-borne noise, Figure 2).

On axial piston pumps of the swashplate type one solution that can virtually break down the flow ripple, and the pressure fluctuations in the hydraulic circuit arising from it, is the use of a pre-compression volume: it consists of an additional oil chamber able to pre-compress the fluid inside each piston before it is delivered to the pressure line.
In order to achieve the prospective benefits of this device, that are the reduction of backflows from the outlet line and the decrease of outlet flowrate peaks, a proper connection between components (Figure 3) must be designed to synchronize the external chamber recharging phase.
A key design feature for an effective result is a proper delivery timing, which is defined by the geometry of the pump valveplate: it decides when and how to connect each pumping piston to external ports and, further complicated, to the pre-compression chamber.
In Casappa R&D Department one simulation tool able to predict the pump functioning is the 1D circuital model depicted in Figure 4, developed in LMS Imagine.Lab AMESim environment in cooperation with the Polytechnic of Turin. This model estimates pump features related to noise as for example piston pressure peak, internal backflows, inlet and outlet flow ripple, cavitation conditions and oscillating forces between inner components.

CASAPPA®
FLUID POWER DESIGN

Figure 1 - MVP series axial piston pump

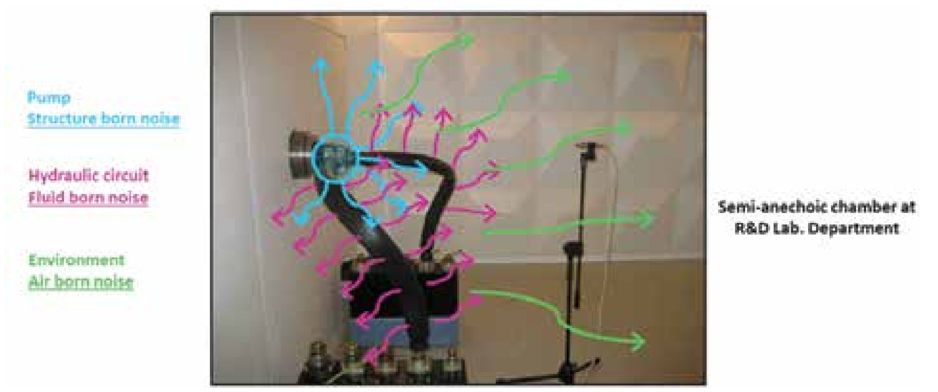


Figure 2 - Sound propagation from the pump

Optimization of the new pump

Once the AMESim model has been updated to consider the presence of the pre-compression chamber, a workflow inside modeFRONTIER software has been created (Figure 5) in order to optimize a new pump with this solution.
Two input variables define the pre-compression chamber volume and connection with outlet line, while other twelve variables fix the valveplate geometry; four constraints on inputs ensure that each configuration can be manufactured.
Two parallel AMESim nodes simulate the pump in five working conditions, combining different ranges of outlet pressure, rotational speed and displacement, in order to be sure that the pump will perform well for each utilization.
The simulation data are post-processed by an Octave script into twelve output variables, expressing the interesting pump performances listed before.

The most influent outputs (internal backflows and flow ripple) have their own objective function for a total amount of 5 OFs, while each other output is constrained according to the restrictive assumption that each feasible design has to be not worse than the current series pump.
A screening analysis of about thousand designs (Figure 6, 1st step) allowed to understand that the performance improvement is proportional to the volume of pre-compression chamber, while the connection with outlet line can be avoided because it slightly affects the OFs.
The valveplate optimization, corresponding to the 2nd step, is composed of a DOE population of 120 designs (30 best configurations from previous simulation + 90 Sobol designs) and a standard Scheduler (MOGA II algorithm, generational evolution, elitism enabled with 25 generations) for a total amount of 3000 designs and 5 days of simulation.
An iterative approach has been chosen, frequently checking and adapting the input variable ranges aiming to follow the optimization algorithm tendency. The final Design Table is composed of 5877 designs, of which only 119 are founded to be feasible.
The optimal solution has been chosen by means of bubble 4D charts (Figure

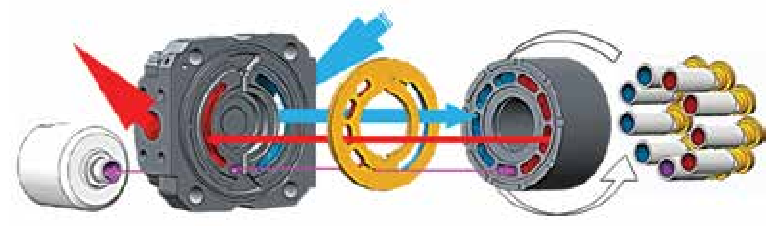


Figure 3 - Connection between pistons, barrel, valveplate, cover and pre-compression chamber

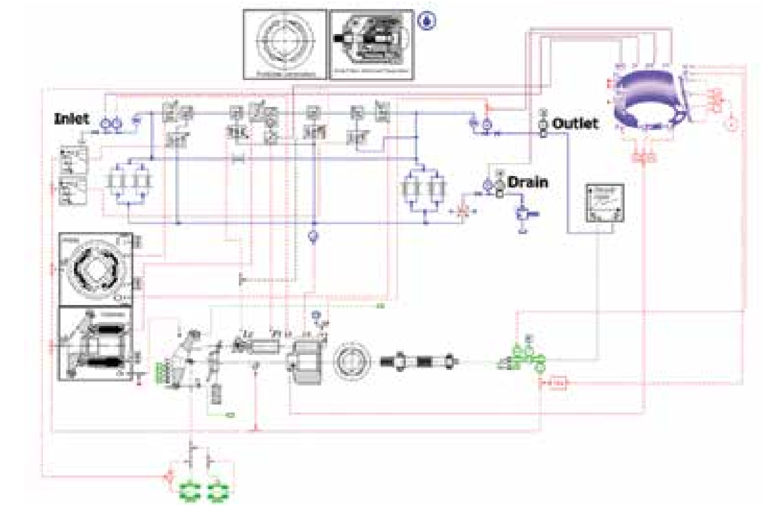


Figure 4 - AMESim model of the MVP60 pump

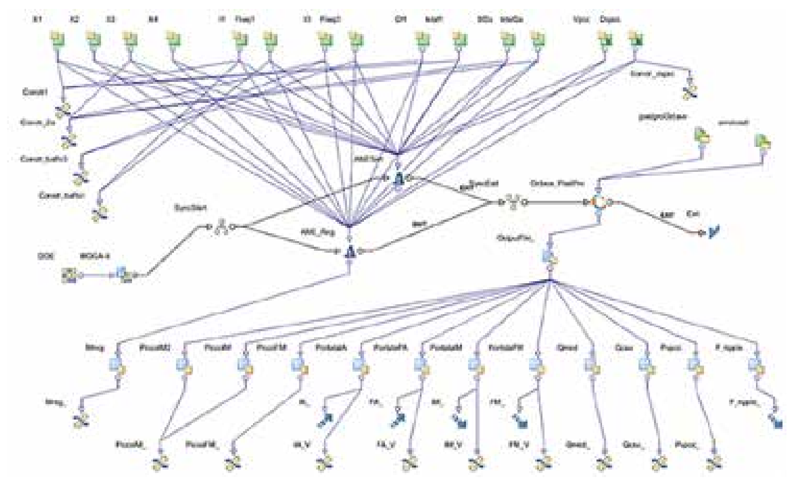


Figure 5 - Optimization workflow

7) and parallel chart filtering: a reduction of 67% and 79% has been achieved on outlet flow ripple and internal backflows (OFs), while all other features have been improved or are unchanged (Figure 8).
In the optimization process it can be noticed that a 4th step was planned for the final refinement: once the optimization was over and the best design identified, a MOGA II has been run restricting the input variable ranges near the optimum combination; this additional step has led to further small improvements (Figure 8).

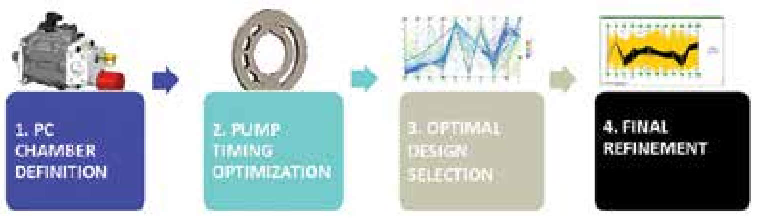


Figure 6 - Optimization process

Prototype and experimental tests

On the basis of the really promising results listed above, the new pump configuration has been prototyped and tested in our Lab Department.
The efficiency levels and cavitation are confirmed to be in line with the current series pump, whereas the pressure ripple highlights a significant lowering, with a maximum reduction on the 1st harmonic of about 71%.
Finally, the most important comparison, the noise emission has been measured in the Lab Department semi-anechoic room according to standard UNI ISO 4412-1:1994: a reduction of 3dB(A) on maximum values has been reached (Figure 9).

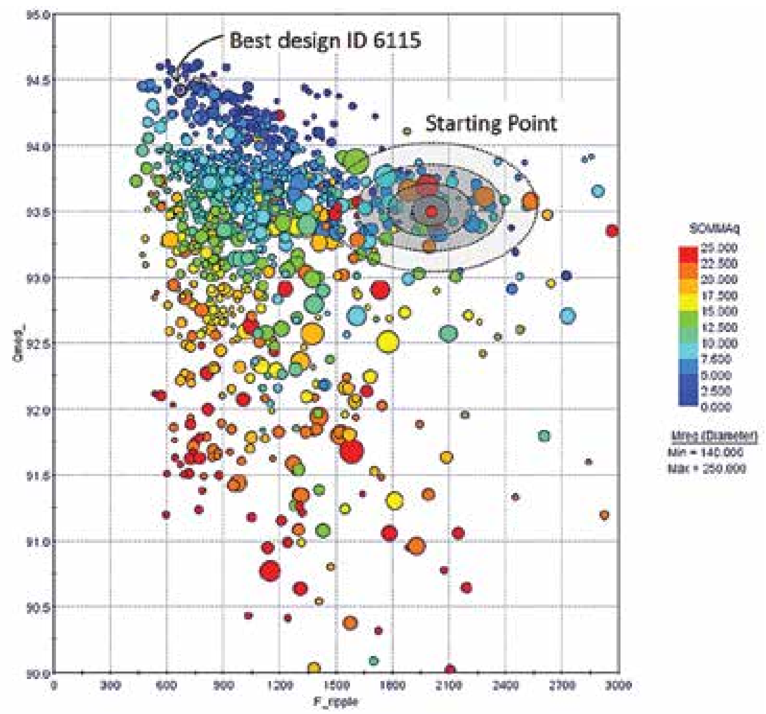


Figure 7 - Optimal design selection

Casappa Spa

Constant evolution and passion for hydraulics! This has been the key to turning the Casappa of 1952, a manufacturer of hydraulic pumps into today's business enterprise. Finrel is the financial holding company owned by the Casappa family that controls companies and subsidiaries
Thanks to the services and skills of its workforce and to investments made in research and development, Casappa is able to design and produce the main hydraulic components for applications in various sectors: construction, industrial vehicles, material handling, agriculture and industry. Besides the supply of standard products, Casappa has chosen to maintain the flexibility required for ad hoc projects, including in small quantities; it is well aware of the importance of being able to closely follow its customers and find timely solutions to their various needs, all of which represents a real stimulus for technological innovation.

Manuel Rigosi, Antonio Lettini - Casappa

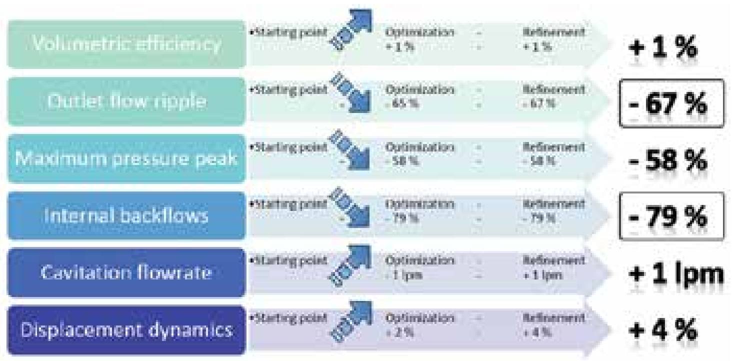


Figure 8 - Final results

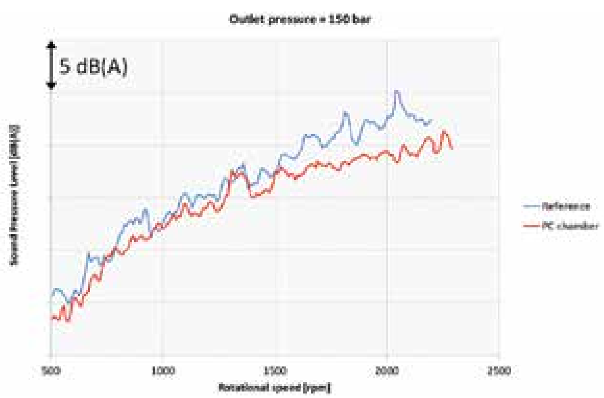


Figure 9 - Sound pressure level comparison

When light is culture: iGuzzini

iGuzzini

Born in 1958, iGuzzini produces interior and exterior lighting devices and today it is the Italian market leader in the lighting engineering and design sector and one of the most important in Europe, with 14 branch offices, almost 1,000 collaborators and a distribution network spread all over the world. iGuzzini mission is not only that of producing high quality lighting devices, but also studying, learning and communicating the importance of light in order to improve its integration with architecture, through industrial design. Furthermore, considering that lighting design is not only spaces illumination, but also being aware of all the different aspects related to the quality of bright interior and exterior environments, iGuzzini collaborates with researchers, doctors, sociologists, physicists, belonging to the most important international Research Centres: Harvard University, M.I.T of Boston, Università "La Sapienza" in Rome, Politecnico of Milan, Central Institute of Restoration, CNR.
iGuzzini develops its concept of "light as element of culture" through activities like cultural sponsorships, workshops, conferences, courses and awards.
In 1995 iGuzzini created its own Investigation and Research Centre, aiming at supporting the cultural debate between the company and the other external entities dealing with light quality: architects, designers, researchers and public audience. For some years now, iGuzzini has been collaborating with Italian schools (from middle schools to universities), organizing informative meetings on light issues and since 2002 it's on line with the e-learning portal "Light Campus".

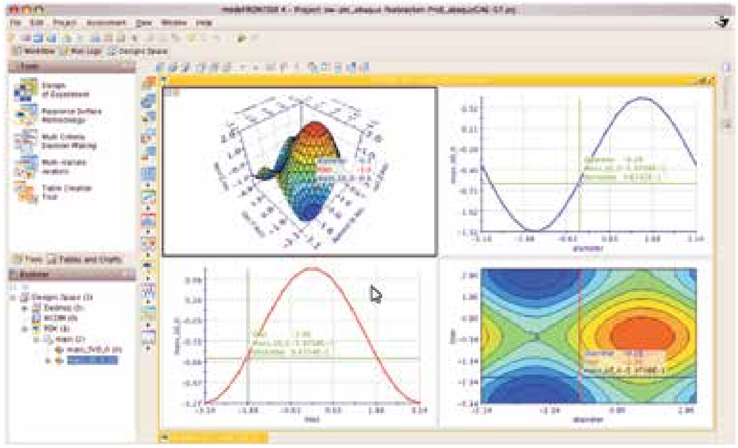
We have heard several "rumors" concerning the benefits provided by modeFRONTIER, in particular from the academia, and for this reason we have decided to invest in this extremely innovative solution, with the expectation of obtaining considerable advantages in terms of product development time and solution quality. We are pretty sure that the application of this tool will enable us to reduce the product development time of the 50% thus evaluating many more design alternatives.

Massimo Gattari
Design Director - iGuzzini

After having invested on ANSYS software some years ago, we have now decided to trust EnginSoft again and to choose its solutions. We are confident that our choice will prove to be the best one, in accordance with our needs and in line with our expectations and policy. iGuzzini lighting has always been a company oriented to best-in-class technology investments so to offer its customers better and better technical solutions and products.

Emidio Alfei
IT Director - iGuzzini

It is extremely important to plan the lighting from the early stages of the architectural project. iGuzzini places its know-how in light organization at all architects' and lighting designers' disposal, providing ideas, light engineering assistance and devices. It has often created ad hoc products and solutions, coming from specific needs of the place to light, that have afterward become part of the iGuzzini production; as for instance the Lingotto in Turin, Renzo Piano's Beaubourg in Paris, or Palazzo Grassi with Aulenti and Castiglioni.



Designing with modeFRONTIER

modeFRONTIER will be used in the lightning engineering, in order to analyse how the lighting system performance can vary in relation with the geometric and lighting design parameters.

In such contexts, due the presence of a high number of variables, the application of modeFRONTIER will allow to better understand the different phenomena and therefore to achieve better performance.

Furthermore, thanks to its full integration with ANSYS, modeFRONTIER will be successfully applied also to the structural sector.

modeFRONTIER Training

EnginSoft offers a wide range of training solutions for modeFRONTIER; both standard and advanced courses are available across Europe. Tailored courses unique to your needs are also available.
www.enginsoft.com

modeFRONTIER Standard Course

This is a two day training course where you can gain first-hand experience of the power of modeFRONTIER. You will learn the necessary workflow methods to conduct multi-objective and multi-disciplinary optimizations while using the latest post-processing tools to data mine your solutions. The course will pay particular attention to multi-objective and statistical problems.

Special attention will be given to practical training on modeFRONTIER's wide range of features, while being supported by the relevant theory on each topic. During the course the following modeFRONTIER applications will be addressed:

- Multi-disciplinary integration and multi-objective optimization in industrial applications;
- Setting up of DOEs (Design of Experiments), data acquisition (from experimental or virtual simulations), derivation of numerical models on acquired data, curve fitting, reverse engineering;
- Multi-objective optimization strategies;
- Statistical analysis, data mining, multi-criteria decision making process and scenario analysis;
- Analysis of robustness and robust optimization:
- Application of RSM (Response Surface Methodology) techniques'.