Newsletter

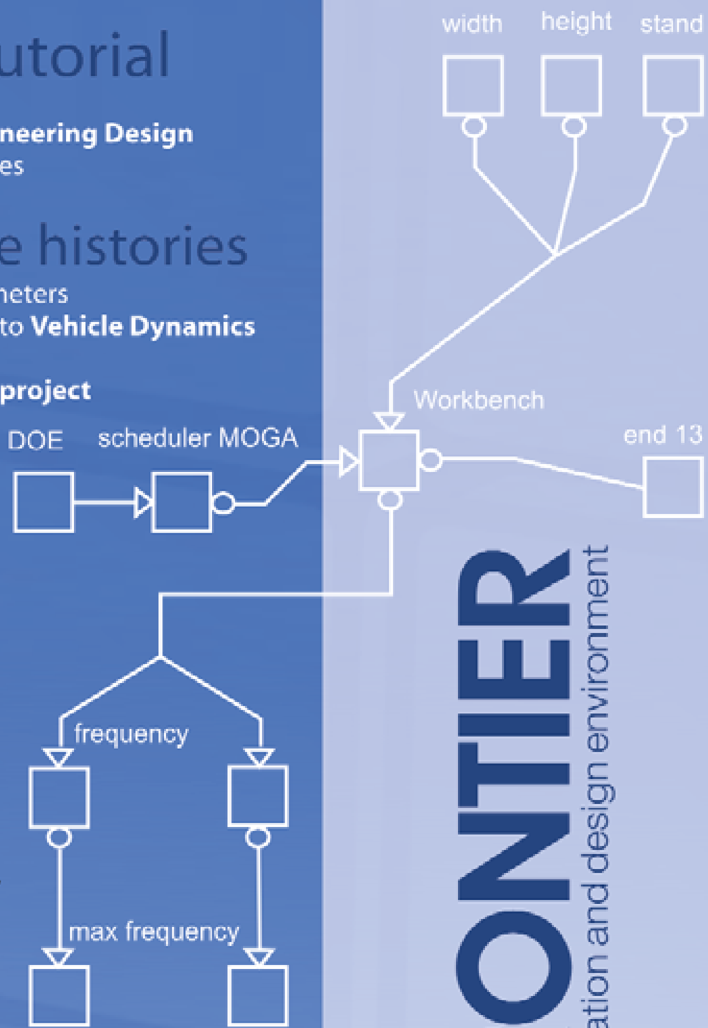
YEAR 4 - modeFRONTIER SPECIAL ISSUE

modeFRONTIER tutorial

modeFRONTIER: Successful technologies for **PIDO**
Multi-objective optimization and decision making process in **Engineering Design**
Meta-modeling with modeFRONTIER: Advantages and Perspectives
modeFRONTIER as a **Statistical Tool**
Design of Experiments

modeFRONTIER case histories

Gear Noise Reduction by numerical optimization of design parameters
Multi-body simulation and multi-objective optimization applied to **Vehicle Dynamics**
Optimization of **Gas Turbine Blades**
Innovative PERM injection system design within the **NEWAC EC project**



modeFRONTIER

the multi-objective optimization and design environment

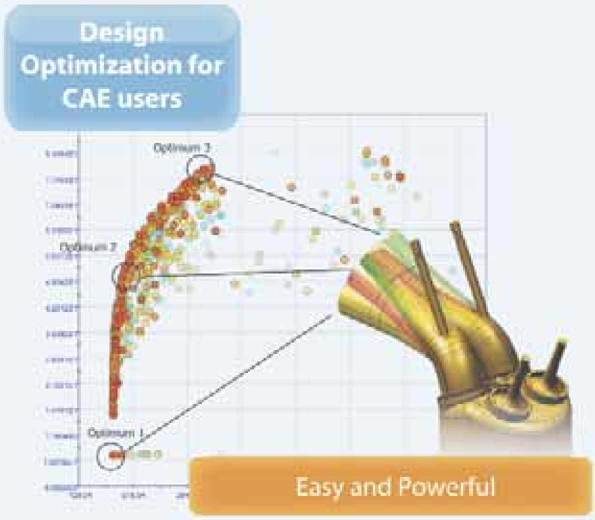
Key partner in Design Process Innovation

modeFRONTIER

the multi-objective optimization and design environment

explore **new frontiers** of innovation

modeFRONTIER is a multi-objective optimization and design environment, written to allow easy coupling to almost any computer aided engineering (CAE) tool, whether commercial or in-house

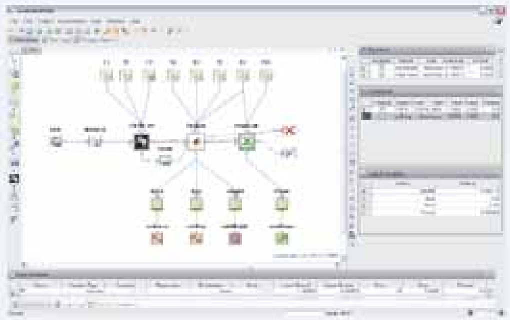


Process Integration

Running an analysis tool within the **modeFRONTIER** framework is extremely straightforward. There are no extra interfaces to license;

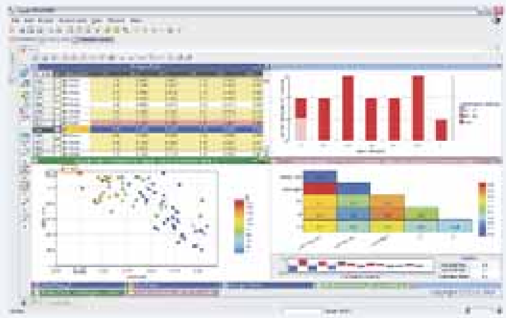
rather just one generic interface which can be used for virtually any CAE tool.
There are also direct interfaces for Excel, Matlab and Simulink; these programs can be used in their own right to perform an analysis, or to control another tool.
The same process integration techniques can be used to link different CAE applications; for example, **modeFRONTIER** has been used to perform a fluid-structure interaction analysis, where a CFD program and a non-linear FEM program were coupled. **modeFRONTIER** has been successfully run with a large number of commercial CAE and in-house tools, ranging from CAD software to FEM and CFD programs.

Coupled Software
modeFRONTIER has been successfully run with many CAE tools, including: Abaqus, Ansys, Adams, AVL-tools, CATIA*, CFX, Excel*, GT-Power, Icem, Kuli, LS-Dyna, Madymo, Magma, Marc, Matlab*, Nastran/Patran, ProjE, Star-CD, Solidworks, Wave, Wamit
(* direct integration nodes)



Design Optimization

With **modeFRONTIER** only few steps are required for achieving your goals
- Describe the problem (parameterize)
- Set goals (objectives)
- Choose the optimization strategy



Using a wide set of DOE (Design of Experiment) and Optimization Algorithms, modeFrontier efficiently searches the design space for the optimum solution, or the Pareto Frontier (set of optimal design in a multi-objective problem)
Select the final design, with the help of modeFrontier's Decision Making tools

modeFRONTIER is a product developed by ESTECO srl - Italy

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modeFRONTIER Community

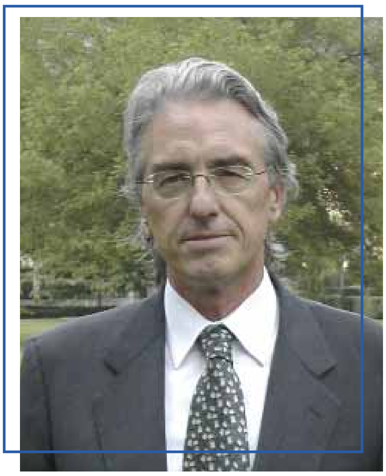
ITALY - GERMANY - UNITED KINGDOM - FRANCE - SPAIN - SWEDEN - JAPAN - FINLAND - NORWAY - TURKEY - PORTUGAL - ISRAEL - USA - AUSTRALIA

Flash

With the annual English edition of the Newsletter, following tradition, we would like to inform our English-speaking readership about EnginSoft, the company, our network, knowledge and expertise in CAE Computer-Aided-Engineering and the services and training related to the technologies we offer.
As most of our readers are familiar with EnginSoft, we decided to dedicate this issue to modeFRONTIER.
modeFRONTIER™ is a multi-objective optimization and design environment technology, developed and produced by ESTECO srl, our partner company headquartered in Trieste – Italy. The following pages provide application examples on the use of the software in aerospace and automotive industries and in the bioengineering sector.

In his interview with Automotive Industries, Carlo Poloni, CEO of ESTECO srl, gives insights into how the software provides the user with an invaluable aid for product design and development. Carlo also speaks about the latest release of modeFRONTIER™, version 4, and its ability to harness large quantities of data, thus bringing sophisticated data mining technology to the desk of designers.
But at a time when science foundations and organisations worldwide emphasize the need for multidisciplinary education, we not only speak about software. We also outline our commitment to education, of how we are delivering the knowledge and benefits of state-of-the-art CAE technologies and simulation to academia and research, areas that are essential for innovation.

The modeFRONTIER™ University Program is a joint initiative of EnginSoft and ESTECO which supports education on campuses across the world. In June 2008, our experts will be conducting a 2-days Training Course for academic specialists at the renowned Trinity College Dublin. At this point, we would like to thank Professor David Taylor of the Mechanical and Manufacturing Department of Trinity, for his collaboration through the years, also in the frame of TechNet Alliance, a global network of CAE experts that we present on the following pages. Our readers will find a summary of the latest publication of David Taylor which he dedicated to the theory of critical distances and failure prediction in this Newsletter.
This time of the year sees our company strongly engaged in the preparations for the EnginSoft Conference 2008 and TCN CAE 2008, the International Conference on Simulation-based Engineering and Science. The bi-annual TCN CAE Conferences represent a moment in time when academia and research meet industry, traditionally at a key venue. TCN CAE 2008 will take place on 16 & 17 October concurrently with the annual EnginSoft Con-ference and the ANSYS Italian Conference 2008. Linked with all canals of the world-famous historic city of Venice, the NH Laguna Palace Hotel boasts Europe's biggest transparent glass roof. Its state-of-the-art conference center and central exhibition area will unify the three events to one of the most important occasions for CAE and simulation in Europe, bringing together the industrial, scientific and educational worlds of simulation.

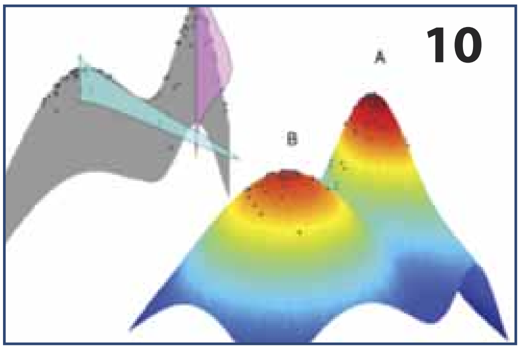


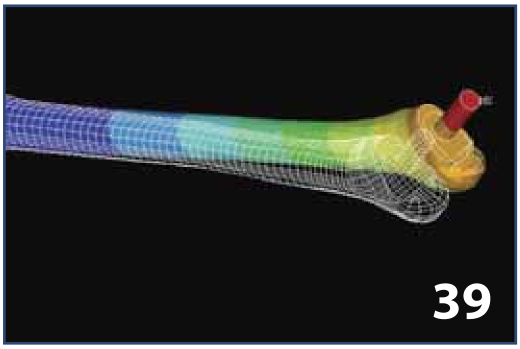
In addition and on 14 & 15 October, the International modeFRONTIER Users' Meeting 2008 will be hosted by ESTECO srl in nearby Trieste allowing attendees to combine their travels to Northeast Italy and to exchange experiences in the application of the software with other users and the program developers.
The modeFRONTIER Community column provides a rich calendar of events informing our readers about the presence of EnginSoft, ESTECO and their partners at conferences, congresses and seminars all over Europe and North America. Furthermore, we have included news from our offices in Frankfurt, Paris and our valued partner in Silicon Valley, Ozen Engineering Inc.

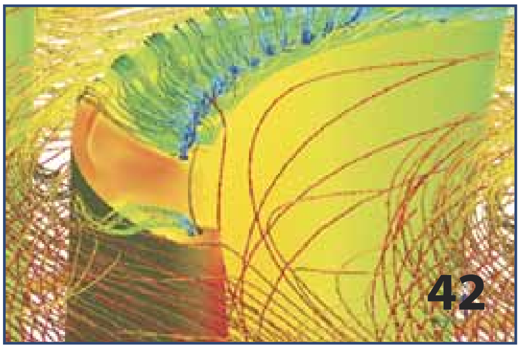
In conjunction with the editorial team, I hope you will enjoy reading this first English Newsletter of 2008. We always welcome feedback, ideas and suggestions to continuously improve the quality of the magazine. So, please do email us any comments you may have.
We also take this opportunity to encourage you to follow our publications on TCN CAE 2008 and the EnginSoft Conference. Please consider to contribute to the success of the events by attending and presenting your work in simulation, a technology sector which many independent studies regard as indispensable for achieving progress in engineering and science in the 21st century.

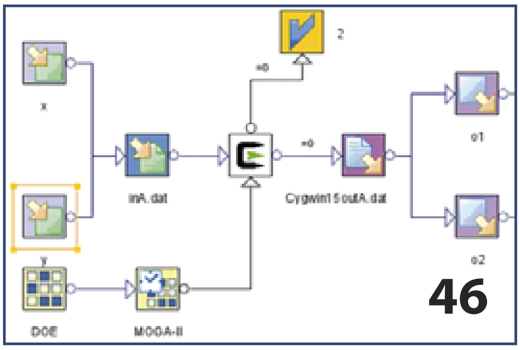
Stefano Odorizzi
Editor in chief

SUMMARY









modeFRONTIER Workshop
Optimizing has never been easier and more powerful

The Workshop will be divided into two parts. The first part will provide a brief description of the product, and an introductory presentation to the latest version 4 of modeFRONTIER. A live demonstration will show how the software works and demonstrate the ease of use and integration with other software tools.

The second part will offer to users a sort of mini-training on the latest capabilities and features of the new version, followed by a session on Q&A. This Workshop is suitable for those with limited or no experience with modeFRONTIER. Anyone involved in research and development, from concept level to production, from CAE to experimental engineers, will benefit from this Workshop.

For more information:
http://meeting2008.enginsoft.it

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Welcome to the modeFRONTIER Network

modeFRONTIER is developed and produced by ESTECO srl, a partner company of EnginSoft.
modeFRONTIER's latest release version 4, provides the user with an even more powerful and user-friendly tool than previous versions. In this context, we recommend to our readers the interview by Carlo Poloni, CEO of ESTECO (see page 8-9) that focuses on the technology and its recent enhancements.

EnginSoft is the main distributor of modeFRONTIER in Europe, Russia, the Middle East and Australia.

It is our primary goal to help our customers, prospects and partners to broaden their knowledge in modeFRONTIER. In order to make these efforts successful, we have established and maintain a network of subsidiaries and partner offices with the aim to provide first-class support and services for the technology.

Our modeFRONTIER operations are managed and directed by ***Giorgio Buccilli*** as Chief Operating Officer. Giorgio's focus is on strengthening business relations between EnginSoft & ESTECO Headquarters in Italy and their partners and customers all over Europe and the Middle East.

Francesco Franchini is the Technical Manager EMEA. As one the first and most experienced modeFRONTIER experts, Francesco is in charge of all technical issues related to sales support.

Luca Fuligno supports the network as Technical Coordinator EMEA. With his extensive expertise in the technology, Luca provides solutions to our partners and customers in all technical matters and gives invaluable support to the network.

Cristina Ancona is the Team Leader of the modeFRONTIER University Program. In her role, Cristina devotes all her know-how and efforts to our collaborations with universities and research institutes across Europe thus encouraging the academia to use modeFRONTIER in numerous research applications.

Luisa Cunico is responsible for marketing, communication and website design. Based in the Italian headquarters, Luisa designs and manages the production of printed and electronic marketing material for the Network. Moreover, Luisa is the Event Manager of the annual EnginSoft Conference and a member of the Newsletter Editorial Team.

Barbara Leichtenstern is in charge of marketing and relations in Europe. Based in Dublin, Ireland, and a native German, Barbara contributes in managing communications, publications, events and networking efforts from the edge of Europe.

The European modeFRONTIER Community represents a network of experts with outstanding engineering expertise EnginSoft and ESTECO are pleased to collaborate with. Our partners in Europe include:

EnginSoft France
www.modefrontier.fr

SIREHNA S.A. www.sirehna.com

ESTECO GmbH Germany
www.esteco.de

CFD Consultants GmbH Germany
www.cfdconsultants.de

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www.esteco.com/northamerica

Ozen Engineering, Inc.
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Supports offices in Sunnyvale, CA - Silicon Valley and at the ICAR campus in South Carolina

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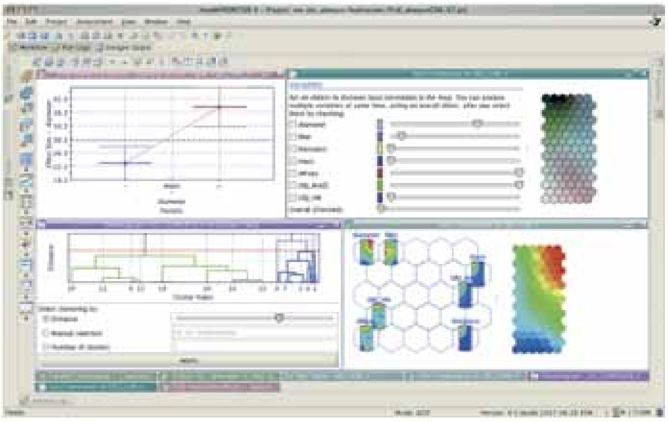
NEW modeFRONTIER™ Version 4: evolving the optimum



ESTECO is proud to announce the release of v4.0 of the multi-objective optimization and design environment software, modeFRONTIER™. This state-of-the-art PIDO tool, written to allow easy coupling to almost any computer-aided-engineering (CAE) tool, is now even more powerful and user-friendly than previous versions.

KEY FEATURES

modeFRONTIER™ v4.0 can handle data sets containing up to 10^6 design configurations, giving rise to the need for enhanced post-processing capabilities:

- Statistical Analysis tools embedded in the system
- Data Mining tools to extract design features
- Wizard to make creation of meta-models easier
- New Look and Feel to enhance navigation between different tools

In addition, modeFRONTIER™ v4.0 contains a wide range of data-mining tools to help understand complex data.

STATISTICAL TOOLS

modeFRONTIER™ features an enhanced set of statistical tools to analyze and exchange data. A Statistic Summary, ANOVA, Significance Analysis, and Distribution Fitting have been added to the extensive list of state-of-the-art tools already in the current version of modeFRONTIER™.

NEW WIZARD MAKES CREATION OF META-MODELS EASIER!

The creation of meta-models (including response surfaces and neural networks) can be a complex and laborious task, especially in situations where high accuracy is required. modeFRONTIER™ v4.0 features a comprehensive wizard which enables the user to create multiple meta-models quickly and automatically. The meta-models are checked for accuracy, allowing the user to select and screen the optimal model.

DATA MINING TOOLS

Analyzing complex data-sets has become easier with the new clustering tools available in modeFRONTIER™ v4.0. Clustering tools, based on Hierarchical and K-Means methods, allow the user to identify, within a data-set, groups of points with similar design features. Self Organizing Maps (SOM) have been introduced to allow the user to analyze and organize data sets by highlighting the most important relationships between inputs and outputs.

DESIGN OPTIMIZATION ALGORITHMS

Other new features have been added to the modeFRONTIER™ framework to make life easier for users when looking for optimal solutions. These include:

- Optimization Wizard, to assist in the selection of the best optimization strategy
- New Multi-Objective Optimizers, including Multi-Objective Particle Swarm (MOPSO)
- Reliability Methods for Robust Design and DFSS
- New automatic work-flow creation: modeFRONTIER™ now features even more seamless integration to third-party CAD/CAE tools.
- Matrix, Vector, and String Variables, to deal with systems of complex data
- New Calculator Node allows advanced post-processing, using built-in functions, to be performed directly in the workflow.

For more information:
www.modefrontier.com

Automotive Industries spoke to Carlo Poloni, CEO of ESTECO

The Italian software company, ESTECO, a world leader in the field of Process Integration and Design Optimization (PIDO) tools, recently announced the release of the latest version of its flagship product, modeFRONTIER™. The foremost multi-objective optimization and design environment for process integration, modeFRONTIER™ provides the user with a set of building blocks to enable the creation of sophisticated workflows to integrate all the software components of a design process, as well as a set of state-of-the-art algorithms (for either single or multi-objective optimization) and extensive post-processing and decision support capabilities. modeFRONTIER™ was born in a European Union project, funded partly by industrial collaborators (such as British Aerospace and Daimler Chrysler Aerospace) and partly by the EU government.

The project, headed by Professor Carlo Poloni, now CEO of ESTECO, addressed the need, primarily in the aerospace industry, for a process integration platform which was also capable of providing true multi-objective optimization and extensive decision-making capabilities. In this respect, modeFRONTIER™, which became a commercial PIDO software in 1999, was at the forefront of the field. Other tools available at the time were solving multi-objective optimization problems by reducing all objectives to a single objective function to be solved using mono-objective algorithms.

modeFRONTIER™ has played a ground-breaking role in spreading the industrial use of multi-objective algorithms, such as genetic and evolutionary methods, and Game Theory. The use of PIDO tools is gaining in popularity as a way to automate and drive simulation-based design processes. Most companies involved in product development already rely heavily on computer aided engineering (CAE) software, such as tools for design (CAD), Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and even proprietary software written within companies to address their particular needs.

Frequently, however, these analyses are run separately from each other; even in the case where the result of one simulation is to be fed to another (an example would be running a CFD analysis to provide thermal boundary conditions for an FEA analysis) there is often a manual process of extracting the data of interest, and passing the file to the user who will perform the next step of the process. Companies are now recognizing that such procedures should be automated in a way which allows all CAE tools to be run without human intervention, and provides for the transfer of the necessary data files between the components.

This is not always a trivial task: in today's environment, product development is often a global activity, distributed among research and development centers in different countries, and even on different continents. It is not uncommon to have CAE tools installed in multiple locations as well; hence process integration in such cases must involve seamless file transfers, using protocols already in place, but avoiding the need for manual entering of passwords, for example. Automating such design processes can be achieved using the process integration part of modeFRONTIER™; the initial set-up of a workflow will take time, as every component has to be tested rigorously to ensure robust performance, but the benefits are immense, since the process can then be run in batch hundreds or even thousands of times for different sets of inputs. The inclusion of a host of direct integration nodes in modeFRONTIER allow the user to easily couple in many of the most widely used CAD and CAE tools.

Once the chain of simulations has been automated, it does not take much extra effort to convert it into an optimization process. The user, having specified which design inputs are to be the variables, will also define certain goals, or objectives; for example, to maximize efficiency and minimize cost. Often in real life applications the goals may be conflicting, which brings us to the concept of trade-off: by keeping the objectives separate, multi-objective optimization frequently gives rise to a Pareto Frontier of designs, all of which can be considered to be candidates for the optimum. In fact, the software got its name from the Pareto Frontier; this is to emphasize the fact that we are dealing with true multi-objective optimization. The fact that modeFRONTIER™ can be used in virtually any field of product development has led ESTECO to forge relationships with a variety of other software suppliers to the automotive industry.

AUTOMOTIVE INDUSTRIES SPOKE TO CARLO POLONI, CEO OF ESTECO

AI: Please help us understand how modeFRONTIER™ helps companies looking for advanced engineering design solutions.

CP: Using the many direct integration nodes, or by employing ASCII files to link other software, the user can easily create a workflow which combines all components of a design process. Once objectives have been defined (e.g. minimize weight, maximize efficiency, etc), and an optimization algorithm selected, modeFRONTIER™ will take over, searching for configurations which provide the best compromise between goals which may well be in conflict. By combining ease-of-use with powerful, state-of-the-art optimization algorithms and process integration techniques, modeFRONTIER™ provides the user with an invaluable aid for product design and development.

AI: How has your affiliation with other software vendors helped ESTECO?

CP: We have both technical and commercial collaborations with 3rd party software vendors; the former involves the creation of direct integrations between their products and ours, while the latter allows those companies also to sell the bundled product (their software together with modeFRONTIER™).

As modeFRONTIER™ is a very "horizontal" product, it is not easy for us to be present in all the markets where it could be used; these relationships give us access to new markets which we might otherwise not penetrate.

AI: How have these partnerships helped modeFRONTIER be more useful to the automotive industry?

CP: Our industrial users, many of whom are in the automotive industry, now have a platform to integrate all their CAE tools; moreover, the ability to directly couple many of the most widely used CAE tools in industry makes the creation of the process workflow significantly easier. It should be remembered that modeFRONTIER™ is, in effect, a robot driving a black box (the analysis programs) which converts inputs (the design variables) into outputs (the metrics by which the system performance can be quantified). For modeFRONTIER™ it is irrelevant whether the programs being driven are Excel, FEA, in-house programs, financial analysis, or a combination of all of these. The easy-to-use and intuitive GUI is the interface to a powerful environment in which to automate design processes, the optimization "driver", and an extensive toolkit of statistical post-processing and decision-making tools.

AI: Please tell us a little more about the new version of modeFRONTIER.

CP: modeFRONTIER™ version 4 is a major release with which we are preparing for the future of simulation. Computer hardware is getting increasingly powerful, and already we see that tremendous computing resources are available for all types of simulation, including co-simulation, as part of the product development process. modeFRONTIER™ 4 is able to harness large quantities of data, and brings sophisticated data mining technology to the desk of designers. This version allows not only optimization but also what we can call "knowledge discovery"; it adds significant new functionality without sacrificing any of the user-friendliness of the previous version.

AI: How popular do you think Version 4 will be to automotive designers? And why?

CP: modeFRONTIER™ 3 was already very popular among both specialist and non-specialist users; I think version 4 will increase even more the acceptance of PIDO tools within the ranks of optimisation experts, CAE users, and upper level decision makers. Managers will be able to exploit detailed information coming from specialists through the integrated design process. For example, a control engineer will be able to exchange information with a mechanical engineer through high-fidelity models integrated in modeFRONTIER™, while the decision maker will be able to add financial considerations to best exploit all the data available.

by Lenny Case

Source:
Automotive Industries, Jan 2008 Issue,
http://www.ai-online.com

modeFRONTIER: Successful technologies for PIDO

The acronym PIDO stands for Process Integration and Design Optimization. In few words, a PIDO can be described as a tool that allows the effective management of the design process and orienting it to the optimum. This kind of tool is becoming more and more important when designing a product as it assists engineers in overcoming the common error of giving priority directly to the product, rather than to the entire process. Although this is unfortunately a common problem, it has been recognized that anything that shortens the time from basic research through product test, process design and production will have an important influence on the overall project quality.

Moreover, many companies today take advantage of virtual prototyping rather than physical testing for the former is usually faster and less expensive. The combination between virtual prototyping and design process makes PIDO an emerging class of tools with the ability to revolutionize product development. The most complete and user-friendly PIDO tool available on the market today, is provided through modeFRONTIER and developed by ESTECO.

Multi-disciplinary design optimization

A multi-disciplinary design process is characterized by subsequent transformations and additions of details. A complete multi-disciplinary design process can be divided into several phases while receiving the contributions of many professional staff and different departments, trying to meet conflicting requirements at the same time. Each phase can be defined as a single module and each single module can be described as a finite group of tightly coupled relationships. These relationships can be under the responsibility of a particular individual or department and may have some variables representing independent inputs or dependent outputs. The single module of a design process usually appears as a "black-box" to other individuals or departments.

Engineers and other specialists are more inclined to push towards improvements of objectives relating to variables of their own discipline which they are able to control directly. In doing so, they usually generate unexpected side effects that other departments and disciplines have to take into account. In most cases, a side effect caused by another discipline generates a decrease of the overall performance. In short, this means that the optimal decision of a single department does not necessarily produce the global optimum of the design process. Roughly speaking, we can say that determining an optimal design within a complex engineering system requires analysis that accounts for interactions between several disciplines.

A PIDO system may indeed support the design of complex engineering systems and of all subsystems. Moreover, a good PIDO tool such as modeFRONTIER, can help engineers in identifying all the relationships between mutually interacting phenomena. modeFRONTIER assists engineers to quickly investigate several design options, to analyze the influence of several reciprocally conflicting goals, and finally, to identify the most robust designs.

A software which really implements PIDO, has to face several complementary aspects globally:

1. The formalization and management of the workflow to treat in a flexible and dynamic way, processes of any complexity grade

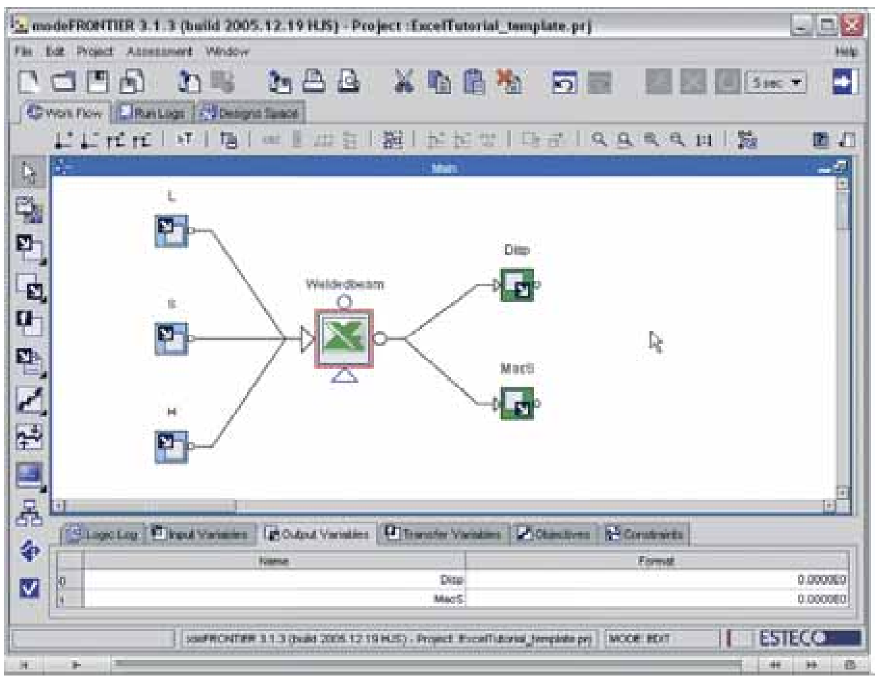


Figure 1: A movie frame from the website, describing direct integration between modeFRONTIER and EXCEL

2. A set of design of experiments and statistical tools to identify which parameters contribute most to the global performance
3. The set of methods, technologies and strategies for multi-objective and multi-disciplinary optimization
4. Meta-modeling and response surface methodologies (RSM)
5. Charts for visualizing the results for easy interpretation
6. The set of the so-called techniques for decision support which allow the orientation and the documentation of choices. From all of the optimal options, the design team must formulate a number of plausible designs.
7. Advanced probability and statistical methods for reliability and uncertainties (design for six sigma)

As this list reflects, a PIDO tool is more a collection of technologies rather than a single software. modeFRONTIER provides all these technologies within an excellent and modern graphical user interface.

modeFRONTIER: a collection of technologies

This section illustrates the technologies involved in a complete PIDO and describes how the same are implemented in modeFRONTIER.

The workflow

The formalization and management of the logic is well guaranteed by modeFRONTIER that allows easy coupling to almost any computer aided engineering (CAE) tool whether commercial or in-house. The formalization of the logic and its workflow cannot be set aside from the integration of the required tools and should be associated with information technology aspects. Indeed, modeFRONTIER is able to deal with processes of any complexity and network organization in a flexible and dynamic way, in the context of distributed and parallel engineering and in presence of local subsystems. modeFRONTIER provides an easy-to-use environment which allows product engineers and designers to integrate and drive their various CAE tools, such as CAD, finite element structural analysis, computational fluid dynamics (CFD) software as well as other multi-disciplinary software. For this purpose, ESTECO has established partnerships with different independent software and hardware vendors. Through these alliances, ESTECO always delivers state of the art industry applications and solutions for multidisciplinary design optimization and system integration. The partnerships include, among others, the ABAQUS Software Alliance, AMESim Partner, ANSYS ESP Program, CD-adapco Software Partner, CST Cooperation Partner, Flowmaster Partner, Linux Networx (LNXI) Partner, as well as the MathWorks Connection Program. By providing a seamless integration with many programs, modeFRONTIER assists in embedding its optimization technology easily in daily work performing both multiple repetitive and concurrent simulations.

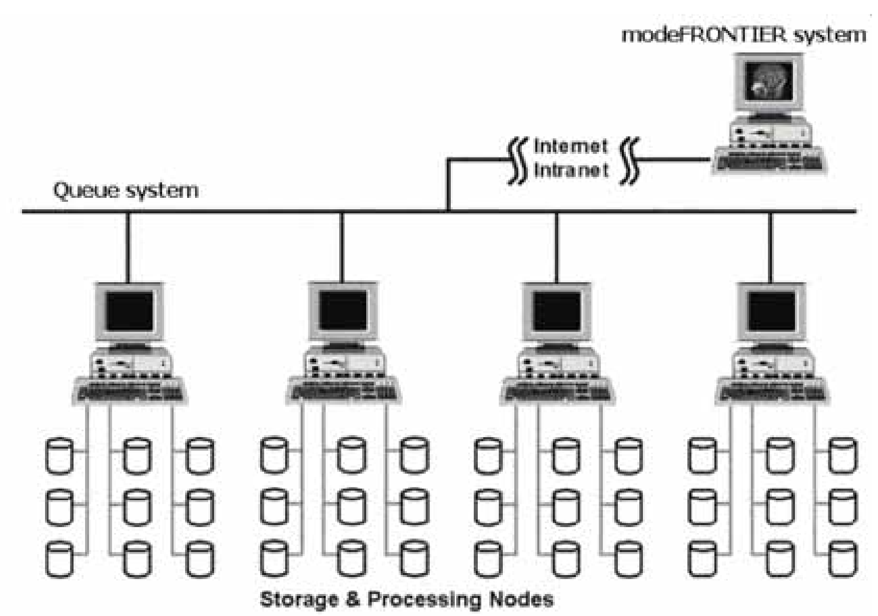


Figure 2: modeFRONTIER coupled with a queuing system, a mixed architecture computer pool can be used to run in parallel several analyses and exploit distributed computing resources

The link "http://www.esteco.com/direct_integration.jsp" provides several examples of how to directly integrate software within modeFRONTIER. Particularly, two interesting animated samples demonstrate how to construct a direct integration with EXCEL and MATLAB in a few steps.

The link http://www.esteco.com/software/queue.jsp shows an example of how to integrate the most famous queuing systems (e.g. Condor) in the modeFRONTIER environment. When using a queuing system, the workflow describes the operation necessary to evaluate a single design. Actually, the whole analysis, or a part of it, can be submitted to a queuing system to be executed in a remote computer. Whenever more than just one computer or CPU is available in the queuing system, more than one design can be executed simultaneously. Moreover, by using a queuing system together with modeFRONTIER, a mixed architecture computer pool can be used to run in

parallel several analyses exploiting a large collection of distributed computing resources thus helping scientists and engineers to increase their computing throughput.
modeFRONTIER does support engineers in managing the IT infrastructure. modeFRONTIER can run software regardless of whether or not it is installed on links together with all CAE tools in a reliable chain-tool.

Design of experiments and statistical tools

The design of experiment (DOE) tool provided in modeFRONTIER can assist in preparing and executing a given number of experiments in order to maximize knowledge acquisition.

When using modeFRONTIER and its methods, users can find several statistical charts and tests, such as, the analysis of variance (ANOVA), Hartley and Bartlett test, Box-Whiskers chart, the multi-range test that shows which means are significantly different from others, a table of means displaying the mean of each along with its uncertainty intervals.
modeFRONTIER provides a "statistics summary" which contains uni-variate descriptive statistics of a parameter along with simple statistical charts and tables. Among others, it contains a frequency plot, probability density and cumulative distribution function charts, as well as a quantile-quantile plot and distribution fitting.

MDO tools

The third item in the list is the element that distinguishes modeFRONTIER from all the other PIDO tools. This element refers to multi-objective and multi-disciplinary optimization (MDO). It is very important to understand the peculiarity of this approach. As the concept of MDO is of great importance, we provide following a brief summary for the completeness of this article.
It is important to recall that the optimum in multidisciplinary contexts with several and often conflicting objectives is not limited to the search for a single absolute extreme of a utility function. This is due to the fact that no utility function is usually able to synthesize a complex phenomenon. With a multi-objective problem, the notion of "optimum" changes as the aim is to find good compromises rather than a single solution. Hence, a multi-objective optimization does not produce a unique solution but a set of solutions. These solutions are called Pareto solutions, the set of solutions can be called both "trade-off surface" or Pareto frontier (named after the economist Vilfredo Pareto).

The first step for a real-world multidisciplinary design optimization is the identification of this frontier. In order to identify the set of good solutions, it is necessary to use the proper algorithms that starting from tentative solutions, allow the evolution towards the optimum. There is not only a single method to solve this problem. The appropriate strategy though has to be verified and applied on a case by case basis, also in connection with the kind of variables considered. For this reason, modeFRONTIER provides a wide range of possible algorithms to choose from for solving different problems.

Moreover, it is possible to combine different algorithms to obtain some hybrid methods. With a hybrid method, we can try to exploit the specific

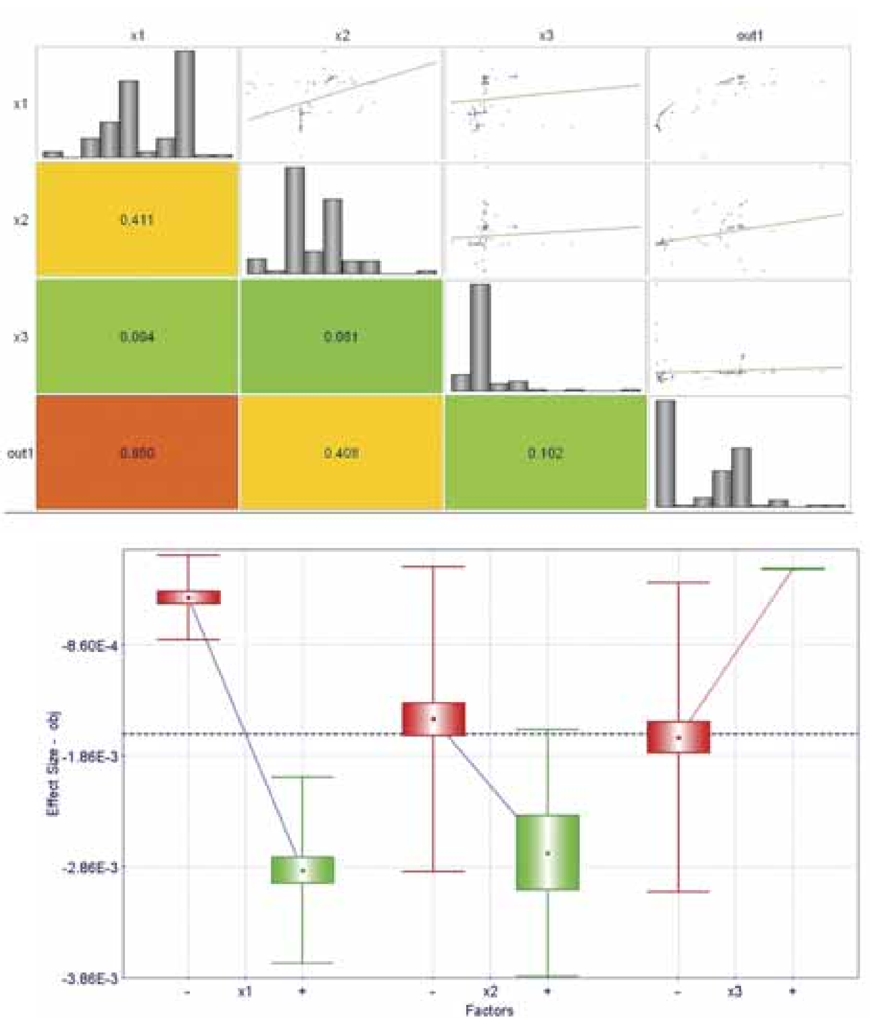


Figure 3: modeFRONTIER statistical chart

advantages of different approaches by linking more than one together. The most common used algorithms for MDO are metaheuristic methods for single and multi-objective optimizations. Metaheuristic methods represent a new type of methods that have been developed since 1980 and are now widely used due to their robustness. These methods have the ability to solve even difficult optimization problems in the best possible way.

Meta-modeling

When considering the advantages and perspectives of interpolation and regression methods and their use in modeFRONTIER, it is important to recall that the use of mathematical and statistical tools to approximate, analyze and simulate complex real world systems is now widely applied in many scientific domains.

These kinds of interpolation and regression methodologies are becoming common even in engineering where they are also known as Response Surface Methods (RSMs). RSMs are becoming very popular as they offer a surrogated model to be used when the original simulation is computationally heavy. A meta-model offers a second generation of improvements in speed and accuracy in computer aided engineering even in cases in which the intensive use of distributed computing resources is not helpful.

Visualizing the results

All PIDOs deal with the problems of visualizing results obtained from multi-disciplinary optimizations. These kinds of problems are usually linked to several dimensions of both, the input parameters and the objectives. modeFRONTIER contains methodologies and charts that simplify and reduce linear and non-linear multidimensional data to much more easy to read charts. Among the most modern tools for this purpose are the so-called Self-Organizing Maps (SOMs) which provide a simplified view of the complex high-dimensional data set. SOMs are particularly useful for data visualization and the classification of databases that appear to be excessively large for human evaluations. Based on the power of such data visualization methods, a new tool has been included into the new release of modeFRONTIER.

Furthermore, modeFRONTIER contains tools for hierarchical and partitive clustering, multi-dimensional scaling, principal component analysis as well as other tools and charts for multi-variate analysis.

Decision support tools

As any good MDO, modeFRONTIER has the ability to look for a complete set of non-dominated solutions. After having found some solutions for the multi-objective optimization problem, engineers obviously find it difficult to select from a given list of choices. Although many efficient solutions exist, only one or a reduced number of final solutions must be finally selected. Multi-Criteria Decision Making (MCDM) refers to the solving of decision problems that involve multiple and conflicting goals. MCDM provides a final solution which represents a good compromise acceptable to everybody involved. The Multi Criteria Decision Making tool provided in modeFRONTIER assists the Decision Maker in finding the best solution from a set of reasonable alternatives. It allows the correct grouping of outputs into a single utility function which is coherent with the preferences expressed by the user without the drawbacks of a weighted function.

Reliability and uncertainties

In real problems, the presence of uncertainties makes the traditional approaches for multi-disciplinary design optimization insufficient. The importance of controlling variability as opposed to just optimizing the expected value has recently started to gain attention within the engineering and scientific communities. Uncertainties in real problems are due to errors in measuring, or difficulties in sampling, or may depend on events and effects in the future that cannot be known with certainty (uncontrollable disturbances

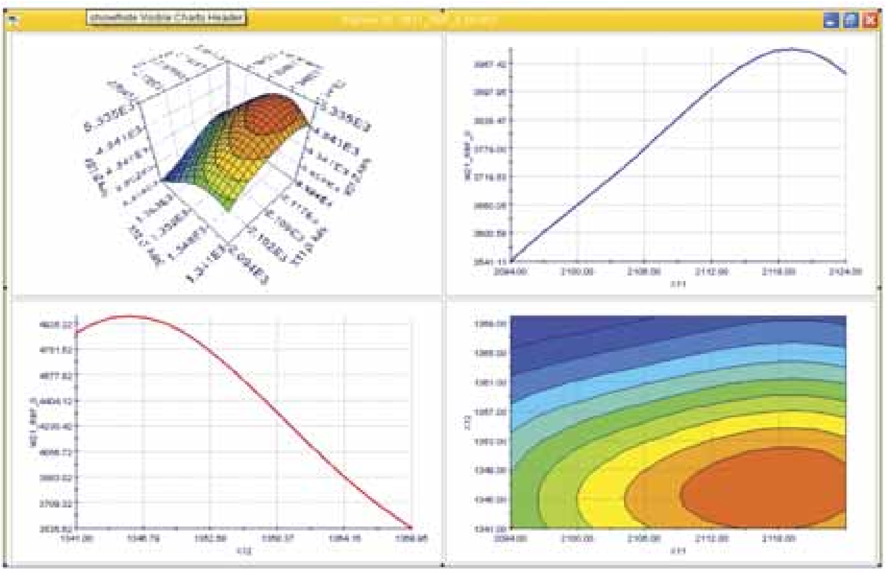


Figure 4: modeFRONTIER tool for meta-models 3D-exploration

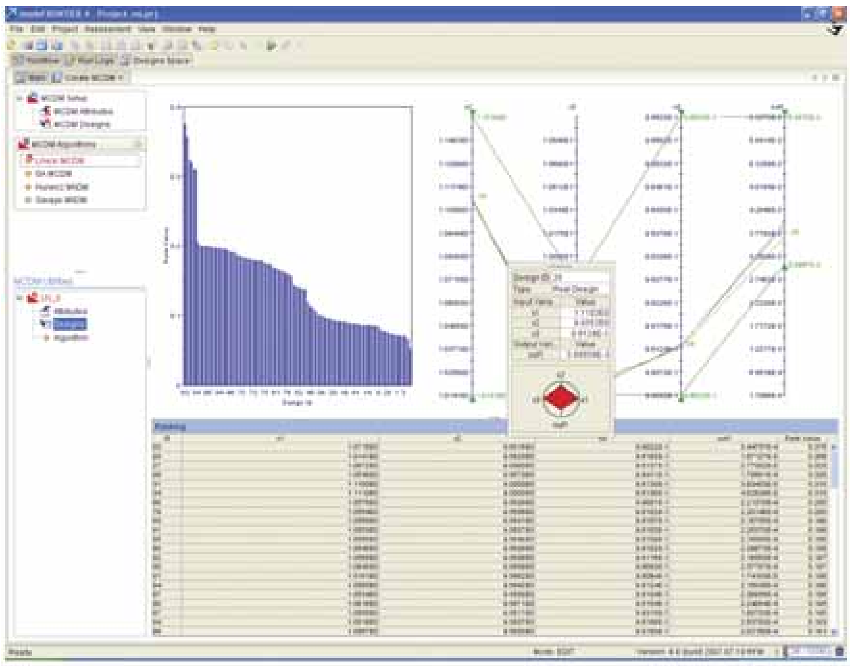


Figure 5: modeFRONTIER tool for supporting Multi-Criteria Decision Making

and forecasting errors). modeFRONTIER covers even these topics. It contains dedicated sampling methods based on Monte Carlo and Latin Hypercube and special statistical charts to verify the reliability of solutions. Moreover, it has a special optimization module named MORDO (multi-objective robust design optimization) that allows the user to perform a robust design analysis to check the system's sensitivity for manufacturing tolerances or small changes in operating conditions.

Conclusions

Nowadays computer technologies have been challenging the environment of engineering design by enabling software tools such as PIDO and MDO systems. This is due to the advances in processor speeds, runtime reduction strategies (parallel computation), powerful disciplinary analyses and simulation programs. The advantages of modeFRONTIER and other PIDOs may be summarized as follows:

- Reduction in design time
- Systematic, logical design procedure. This ensures the launching of innovative quality products to the market thus improving the brand images of all companies using these technologies
- Ability to handle wide ranges of design variables and constraints
- Not biased by intuition or experience

References

[1] Design of Experiments – EnginSoft Newsletter – Anno 3 – n. 4 – Inverno/winter 2006

[2] Multi-objective Optimization and Decision Making Process in Engineering Design – EnginSoft Newsletter – Anno 4 – n. 1 – Primavera/spring 2007

[3] Meta-modeling with modeFRONTIER: Advantages and Perspectives – EnginSoft Newsletter – Anno 4 – n. 2 – Estate/summer 2007

The websites, www.esteco.com and www.network.modefrontier.eu provide several examples of how to apply PIDO technologies in Engineering Design. For any questions on this article or to request further examples or information, please email the author:

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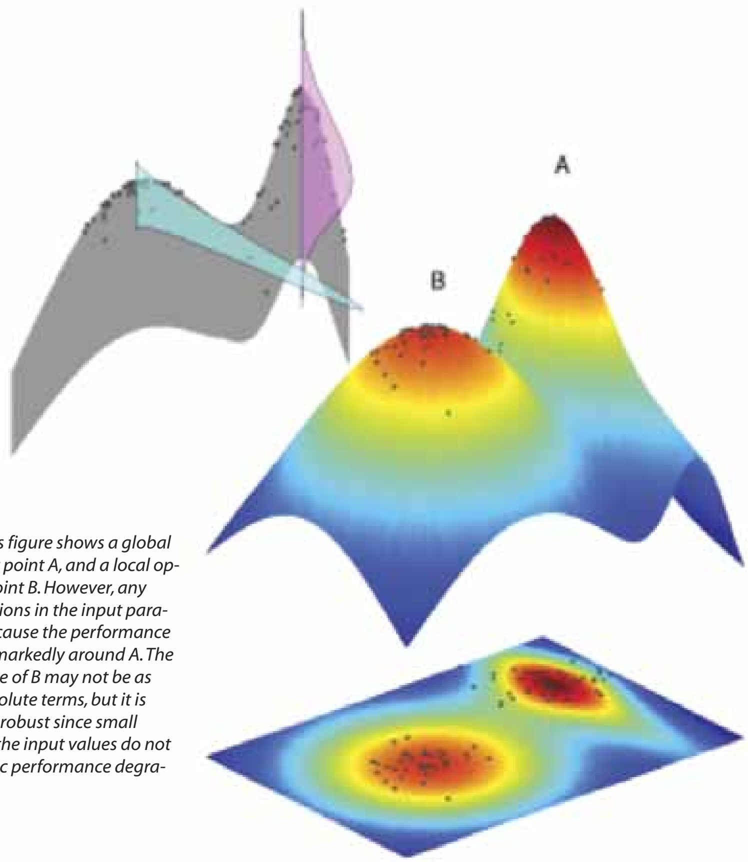

Figure 6: this figure shows a global optimum at point A, and a local optimum at point B. However, any small variations in the input parameters will cause the performance to drop off markedly around A. The performance of B may not be as good in absolute terms, but it is much more robust since small changes in the input values do not cause drastic performance degradation.

Multi-objective optimization and decision making process in engineering design

Companies need to optimize their products and processes daily, hence optimization plays a significant role in today's design cycle. Problems related to one or more than one objective, originate in several disciplines; their solution has been a challenge to engineers for a long time. Typically using a single optimization technology is not sufficient to deal with real-life problems. Therefore, engineers are frequently asked to solve problems with several conflicting objective functions. The definition of Multi-disciplinary optimization given by the Multi-Disciplinary Optimization Technical Committee of the American Institute of Aeronautics and Astronautics (AIAA) is self-explaining. The definition states: "Optimal design of complex engineering systems which requires analysis that accounts for interactions amongst the disciplines (or parts of the system) and which seeks to synergistically exploit these interactions".

Multi-objective optimization

It is difficult to explain optimization techniques in a few words; there are plenty of books describing different methods and approaches.

Roughly speaking, to optimize means selecting the best available option from a wide range of possible choices. This can be a complex task as, potentially, a huge number of options should be tested when using a brute force approach. There are several sources of complexity, such as the computational difficulties in modeling the physics, the potentially high number of free variables, or a high number of objectives and constraints. Moreover, the coupling between disciplines can be challenging, involving several complicating factors, such as the limitation on the computational resources, restrictions connected with the algorithms' capabilities and even a lack of communication between different departments. Often, engineers are so committed to a single position that they lack an overall picture of the optimization problem. Anyhow, the design analysis can be decomposed into different levels, where each "sub-structure" can be approached and optimized in a similar way. By using design automation procedures, the entire design process or the specific sub-problems can be analyzed systematically, by means of:

- Design of Experiments
- Optimization Algorithms
- Decision-Making Procedures

In a previous article, we explained how the Design of Experiments tool can help in preparing and executing a given number of experiments in order to maximize knowledge acquisition. In this article, we focus on optimization algorithms and decision making procedures.

In order to help engineers and decision makers, old and new optimization techniques are studied and widely used in industries. Each optimization technique is qualified by its search strategy that implies the robustness and/or the accuracy of the method. The robustness of an optimization method is the ability to reach the absolute extreme

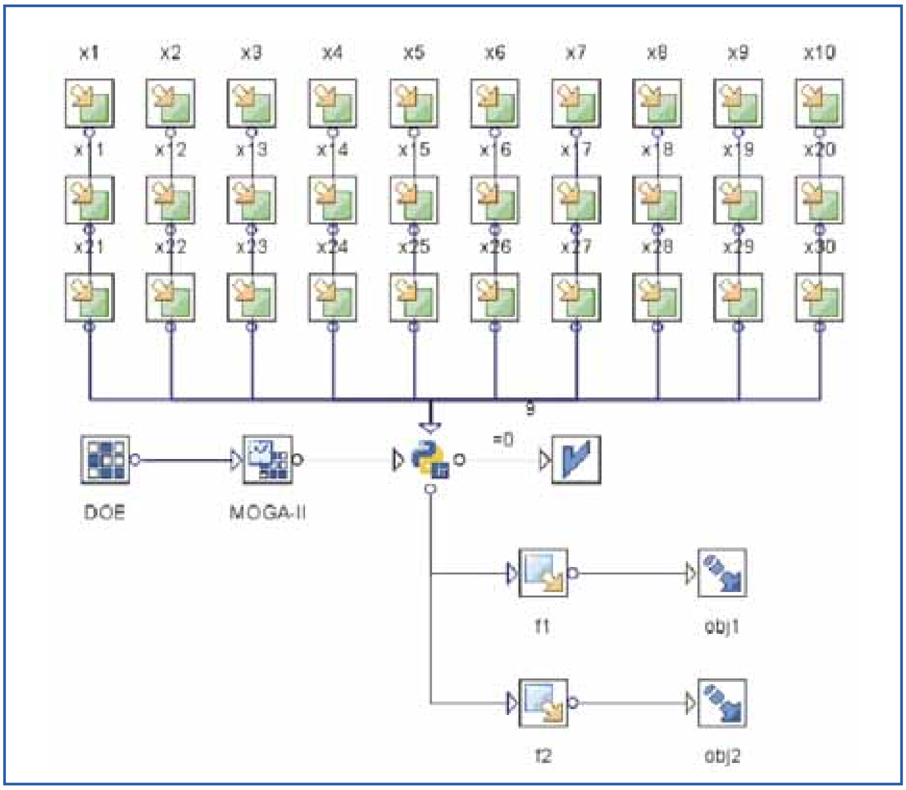

Figure 1: modeFRONTIER workflow describing a well-known ZDT1 multi-objective problem. This problem has 30 continuous input variables and two objectives. A complete description of this problem can be found in K. Deb's, "Multi-Objective Genetic Algorithms: Problem Difficulties and Construction of Test Problems", Evolutionary Computation, 7(3):205-230.

of the objective function even when starting far away from the final solution. On the contrary, the accuracy measures the capability of the optimization algorithm to get as close as possible to function extreme. There are hundreds or thousands of optimization methods in literature, each numerical method can solve a specific or more generic problem. Some methods are more appropriate for constrained optimization, others may be suitable for unconstrained continuous problems, or tailored for solving discrete problems. A lot of “classical” optimization methods exist; these methods can be used provided that certain mathematical conditions are satisfied. Thus, for example, linear programming efficiently solves problems where both the objective and the constraints are linear with respect to all the decision variables. Other specific numerical methods can be useful for solving quadratic programming, nonlinear problems, nonlinear least squares, nonlinear equations, multi-objective optimization, and binary integer programming. Unfortunately, real world applications often include one or more difficulties which make these methods inapplicable. Most of the time, objective functions are highly non-linear or even may not have an analytic expression in terms of the parameters.

The mathematical formulation of a general multi-objective optimization problem can be written as follows:

$$\min\left[f_1(x_1,\ldots,x_n), f_2(x_1,\ldots,x_n),\ldots,f_k(x_1,\ldots,x_n)\right]$$
$$\text{subject to}\begin{cases} g_i(\bar{x})\geq 0 \\ g_j(\bar{x})=0 \\ \bar{x}\in S \end{cases}$$

When k>1 and the functions are in contrast, we speak about multi-objective optimization. (x1, …, xn) are the variables, the free parameters, i.e. the quantities that the designer can vary. It is by modifying these values that the search for an optimum is performed. The variables can be continuous or discrete. The problem may even contain a mixture of continuous and discrete variables. This does not pose any extra difficulties in setting the optimization problem up, however, it may slightly restrict the user's choice of search algorithms.

Adopting a model with a large number of input variables may appear to give more freedom of choice for the final design. However, the more dimensions the parameter space implies, the more work will be involved in searching the space for optimum designs. In practice, the work and hence the computational cost, snowball as the number of parameters increases.

(f1,…,fk) are the objective functions, the response parameters. These are the quantities that the designer wishes to maximize or minimize. For example, the designer can maximize the efficiency, the performance, or can minimize the cost, the weight. In multi-objective optimization problems, there are three possible situations: minimize all the objective functions, maximize all the objective functions, or minimize some and maximize others. For simplicity reasons, usually all the functions are converted to maximization or minimization form. Hence a maximization problem can always be transformed into a minimization problem with the following identity:

max fi(x) = -min(-fi(x))

Gi(x) are the constraints. Equality and inequality constraints are the quantities imposed on the project, i.e. restrictions and limits that the designer must meet due to the norms, or by the particular characteristics of the environment, functionalities, physical limitations, etc. These restrictions must be satisfied in order to be able to consider a certain solution as acceptable. All the constraints define a feasible region. The designer can impose some general constraints such as the maximum

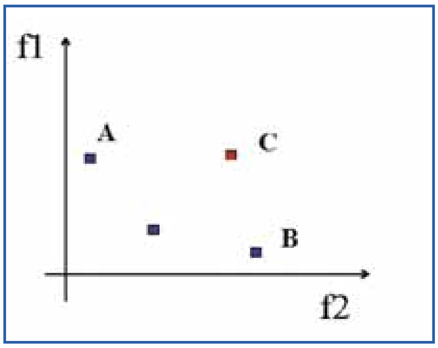

Figure 2: The concept of Pareto dominance. Point C is dominated by points A and B. A and B are better than C both for objective f1 and objective f2. A does not dominate B and B does not dominate A because A is the best point with respect to objective f2 and B is the best one with respect to objective f1. Hence, A and B are non-dominated and efficient solutions.

admissible stress, the maximum deformation, the minimum performance. Or the designer can even impose some special constraints on the variables such as the total volume, the range for the thickness, and so on.

With a multi-objective problem, the notion of “optimum” changes as the aim is to find good compromises rather than a single solution. So, a multi-objective optimization does not produce a unique solution but a set of solutions. These solutions are called Pareto solutions, the set of solutions can be called both “trade-off surface” or Pareto frontier.

In the Pareto frontier, none of the points are “dominated”. By definition we say that the design a dominates design b if:

[f1(a) <= f1(b) and f2(a) <= f2(b)
…and fk(a) <= fk(b)]
and [f1(a) < f1(b) or f2(a) < f2(b)
…or fk(a) < fk(b)]

Roughly speaking, we can say that in the Pareto frontier none of the components can be improved without deterioration of at least one of the other components. Figure 2 shows the concept of Pareto optimal dominance in a 2-dimensional space. Pareto optimal solutions are also known as non-inferior, non-dominated or efficient solutions. These solutions may have no clear relationship besides their membership in the Pareto optimal set. Moreover, it may be difficult or even impossible to find an analytical expression of the surface that contains all these efficient points.

modeFRONTIER is a very powerful tool for multi-objective optimization, and it includes the most widely used methods. It offers an easy-to-use graphic user interface for describing the problem as shown in Fig. 1. modeFRONTIER contains both "classic" and metaheuristics methods for single and multi-objective optimizations. Metaheuristics methods are a new type of methods that have been developed since 1980. These methods have the ability to solve even difficult optimization problems in the best way possible. This is an important group of methods that has significantly contributed to the renewal of multi-objective optimization. Before, multi-objective optimization problems were solved only by means of weighted functions with which the problem is transformed into a single objective problem using weights wi:

F(x) = w1*f1+w2*f2+…+wk*fk

This formulation seems to be very simple and easy to understand although it may seem like adding apples and oranges. And unfortunately, this simple formulation has several drawbacks. First of all, the weights are problem-dependent and must be empirically defined by the user. The user should even take care of normalization and this can be as complex as the global optimization because the range of variation of each function may be unknown. Last but not least, summing up functions even means summing up discontinuity. Until recently, considerations of computational expense forced users to use only this kind of weak approach. However, newer and more ambitious approaches such as the so-called metaheuristics methods aim to optimize several objectives simultaneously, thus generating various points in the Pareto set. The class of methods includes among others: simulated annealing, genetic algorithms, particle swarm, ant colonies, evolutionary strategies, tabu search. They have some characteristics in common, such as to be at least partly stochastic and not to require to compute derivatives. Moreover, they are inspired by analogies with physics, or with biology or with ethology. Unfortunately, they even share the same drawback which is, usually, the high computation time required for convergence. This should be considered as the price to be paid in order to have a robust method that has the ability to overcome the obstacle of local optima. This problem is partially solved by the parallelization: in recent years, several ways of parallelizing various metaheuristics have been proposed.

All these metaheuristics are not mutually exclusive. It is often impossible to predict with certainty the efficiency of a method when it is applied to a problem. This statement is confirmed by the well-known "no-free-lunch theorem" (NFLT) developed by D. Wolpert and W. Macready. The theorem states that "[...] all algorithms that search for an extremum of a cost function perform exactly the same, when averaged over all possible cost functions."

For this reason, modeFRONTIER includes a wide range of possible algorithms that can be selected for solving different problems. At present, the methods available in modeFRONTIER are:

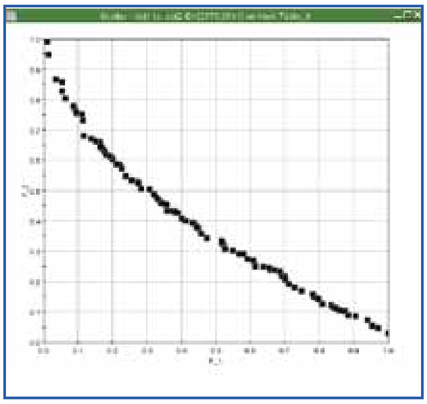

Figure 3: Pareto frontier of the ZDT1 obtained by using MOGA-II.

- SIMPLEX
- Bounded-BFGS
- Levenberg-Marquardt
- Simulated Annealing
- Multi-Objective Genetic Algorithm (MOGA)
- Adaptive Range MOGA
- Multi-Objective Simulated annealing (MOSA)
- Non-dominated Sorting Genetic Algorithm
- Multi-objective Game Theory
- Fast MOGA
- Fast SIMPLEX
- Evolutionary Strategies Methodologies
- NLPQLP
- Normal Boundary Intersection (NBI)

Moreover, different algorithms can be even combined to obtain some hybrid methods. An hybrid method can try to exploit the specific advantages of different approaches by combining more than one together. For example, it is possible to combine the robustness of a genetic algorithm together with the accuracy of a gradient-based method, using the former for initial screening and the latter for refinements. Whenever possible, modeFRONTIER's algorithms can be used in parallel, to run more than one evaluation at once and to take advantage of available queuing systems.

Multi-Criteria Decision Making (MCDM)

As shown in figure 3, modeFRONTIER can look for a complete set of non-dominated solutions. However and obviously, after having found some solutions of the multi-objective optimization problem, we are facing some difficulties: although many efficient solutions exist, only one or a reduced number of final solutions must be selected.

As it is impossible to order the full range of available designs (at once), all Pareto optimal solutions can be regarded as equally desirable in the mathematical

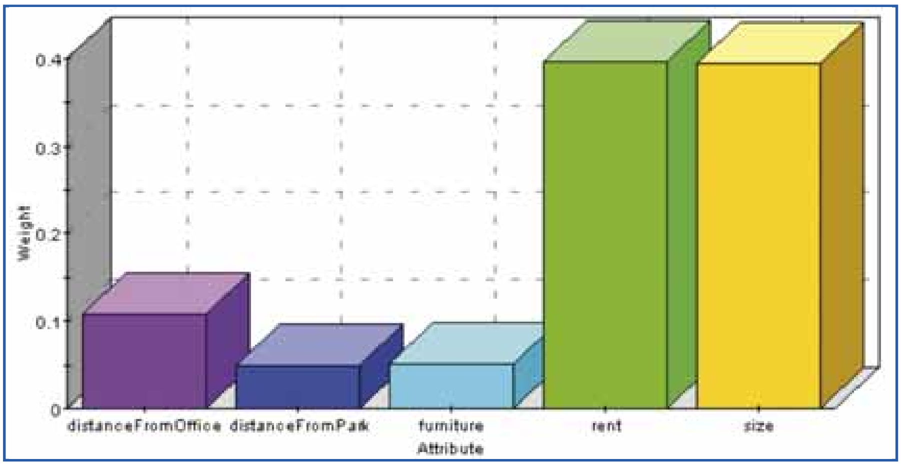

Figure 4: Decision Making example: Choosing a flat to rent on the basis of the following criteria: size, rent, distance from the office, distance from open spaces such as parks and quality of the furniture. The DM can express pair-wise relationships between attributes such as "rent is twice more important than distance from open spaces" and "distance from the office is twice more important than distance form the nearest park". This chart shows the automatic weights generated by modeFRONTIER according to DM choices, the final ranking depends on these weights.

sense. Hence, we need decision makers (DMs) to identify the most preferred one among the solutions. The decision maker is a person who is able to express preference information related to the conflicting objectives.

Ranking between alternatives is a common and difficult task, especially when several solutions are available or when many objectives or decision makers are involved. The decision makers choose one reasonable alternative from a limited set of available ones; design decisions usually reflect the competencies of each decision maker. When more than one decision attribute exists, making coherent choices can be a very difficult task.

Multi-Criteria Decision Making (MCDM) refers to the solving of decision problems involving multiple and conflicting goals, coming up with a final solution that represents a good compromise that is acceptable to the entire team. modeFRONTIER Multi-Criteria Decision Making allows the user to classify all the available alternatives through pair-wise comparisons on attributes and designs. Moreover, modeFRONTIER helps decision makers to verify the coherence of relationships. To be coherent, a set of relationships should be both rational and transitive. To be rational means that if the decision maker thinks that solution A is better than solution B, then solution B is worse than solution A. To be transitive means that if the decision maker says that A is better than B and B is better than C, then solution A should be always considered better than solution C.. So, we can say that the Multi Criteria Decision Making tool provided in modeFRONTIER assists the Decision Maker in finding the best solution from a set of reasonable alternatives. It allows the correct grouping of outputs into a single utility function that is coherent with the preferences expressed by the user and it does not have the same drawbacks of a weighted function.

The following algorithms are actually available in modeFRONTIER:

- Linear MCDM to be used when the number of decision variables is small;
- GA MCDM which does not perform an exact search but is more efficient than the previous method.
- Hurwicz used for uncertain decision problems. This criterion represents a compromise between the maximax and maximin criteria. The decision maker is neither optimistic nor pessimistic. With this criterion, the decision attributes are weighted by a coefficient that is a measure of the decision maker's optimism. For example, when the Hurwitz weight is equal to zero, the maximax criterion is used. With this criterion, the decision maker selects the design that represents the maximum of the best attribute. On the contrary, when the Hurwitz weight is equal to one, the reverse approach to the maximax criterion is used. The maximin criterion is based on the assumption that the decision maker is pessimistic about the future. With this criterion, the minimum value of the attributes for each designs are compared, and the design that produces the maximum of the minimum value must be chosen;
- Savage MADM used for the uncertain decision problems where both the decision states and their likelihoods are unknown. This algorithm examines the regret (i.e. losses) resulting when the value of the selected alternative is smaller than the optimized value. Then, the minimax criterion suggests that the decision maker should look at the maximum regret of each strategy selecting the one with the smallest value.

Conclusions

The website www.esteco.com contains several examples of how to use Multi-Objective Optimization and Decision Making Process in Engineering Design. Most of the examples are slanted towards applications in fluid dynamics. However, this only reflects some of the research interests of the original authors since multi-objective optimization problems and the coupling of these techniques with modeFRONTIER can be much more general.

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Meta-modeling with modeFRONTIER: Advantages and Perspectives

The progresses in finite elements methods (FEM) and high performance computing offer to engineers accurate and reliable virtual environments to explore various possible configurations. On the other hand and at the same time, the number of users' requests constantly increases going even beyond computational exhaustiveness.

In real case applications, it is not always possible to reduce the complexity of the problem and to obtain a model that can be solved quickly. Usually, every single simulation can take hours or even days. In such cases, the time frame required to run a single analysis, prohibits running more than a few simulations, hence other, smarter approaches are needed.

Engineers may consider and apply a Design of Experiment (DOE) technique to perform a reduced number of calculations. These well-distributed results can be subsequently used by the engineers to create a surface which interpolates these points. This surface represents a meta-model of the original problem and can be used to perform the optimization without computing any further analyses.

The use of mathematical and statistical tools to approximate, analyze and simulate complex real world systems is widely applied in many scientific domains. These types of interpolation and regression methodologies are now becoming common even in engineering where they are also known as Response Surface Methods (RSMs). RSMs are indeed becoming very popular as they offer a surrogated model with a second generation of improvements in speed and accuracy in computer aided engineering.

Interpolation and regression methods for computer aided engineering

Constructing a useful meta-model starting from a reduced number of simulations is by no means a trivial task. Mathematical and physical soundness, computational costs and prediction errors are not the only points to be taken into account when developing meta-models. Ergonomics of the software have to be considered in a wide sense. Engineers would like to grasp the general trends in the phenomena, especially when the behavior is nonlinear. Moreover, engineers would like to re-use the experience accumulated, in order to spread the possible advantages on different projects. When using meta-models, engineers should always keep in mind that this instrument allows a faster analysis than complex engineering models, however, interpolation and extrapolation introduce a new element of error that must be managed carefully.

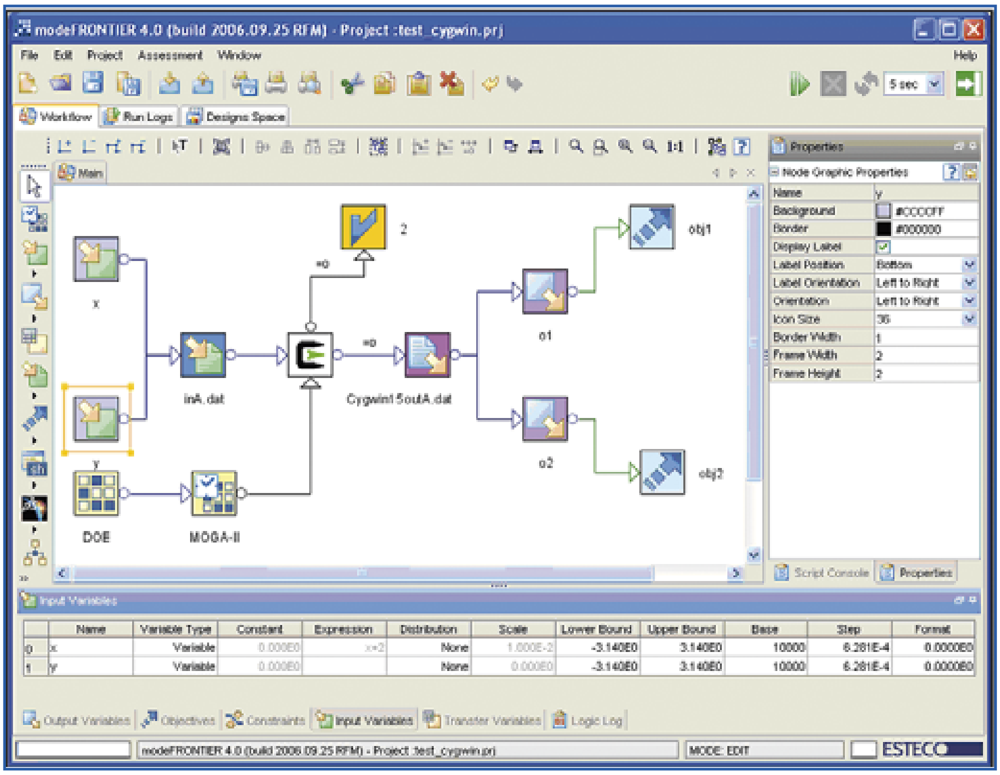

Figure 1: modeFRONTIER panel which helps engineers to easily formulate the problem, design the objectives and constraints, and identify the input and output parameters.

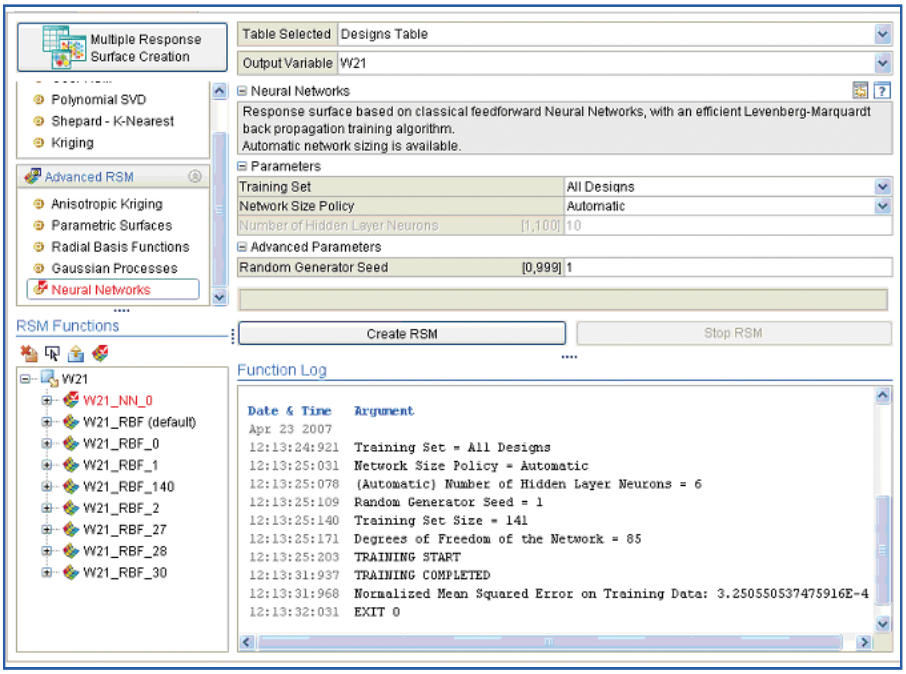

Figure 2: modeFRONTIER panel with which engineers can easily formulate, generate and save several kinds of meta-models.

It is for these reasons that in the last years, different approximation strategies have been developed to provide inexpensive meta-models of the simulation models to substitute computationally expensive modules. The intention of this article is to demonstrate particular features of modeFRONTIER that allow an easy use of the meta-modeling approach.

A typical sequence when using meta-models for engineering design can be summarized as follows:

1. First of all, engineers should formulate the problem, design the objectives and constraints, and identify the problem's input and output parameters; this may include specifying the names and bounds of the variables that will be part of the design, as well as characterizing the responses. This is quite an easy task in modeFRONTIER; the user can take advantage of all the features and the node of the workflow [fig.1]. At this step, it is also advisable to determine whether the use of a meta-model is justified, or whether the analysis should be conducted with the original simulation instead.

2. If the original simulation is computationally heavy and the use of the meta-model is necessary, the designer should choose the number and type of designs at which it would be more convenient to run the original simulation model. The true output responses obtained from these runs are used for fitting the meta-model. Even though this step is quite an easy task in modeFRONTIER, the user can take advantage of all the methodologies available in the Design of Experiment tool.

3. At this point, the engineer can use the output responses obtained in the previous step for fitting the meta-model. The fitting of meta-models requires specifying the type and functional form of the meta-model and the easy-to-use interface to save, evaluate and compare different responses. modeFRONTIER assists engineers even at this important step by means of its Response Surface Methodologies tools (RSMs) [Fig. 2].

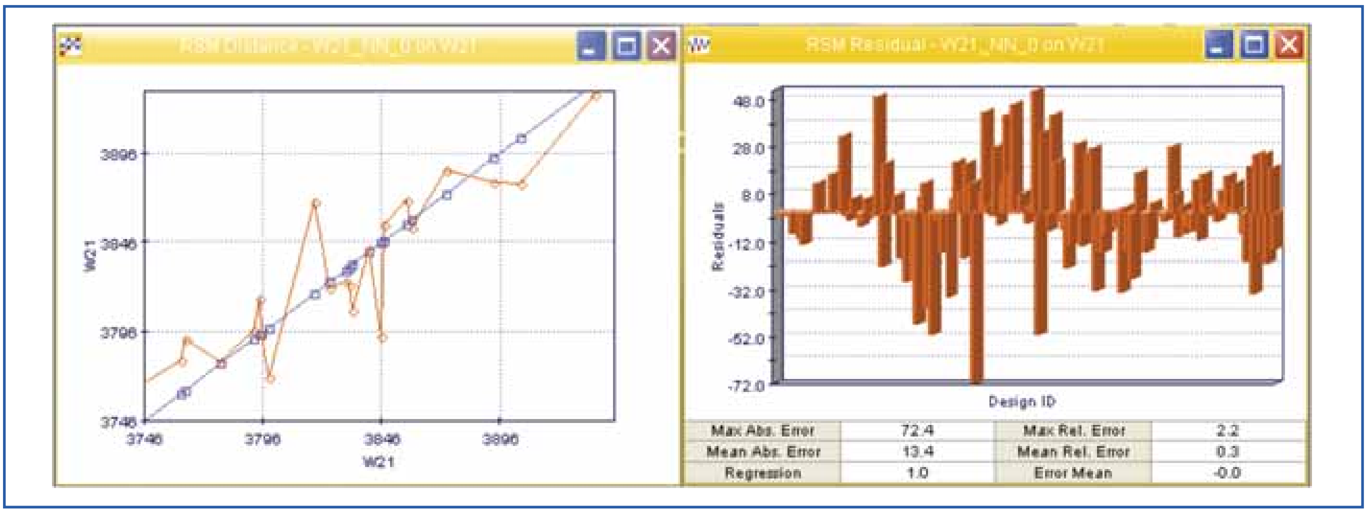

Figure 3: Distance chart (left) and residual chart (right). These charts represent two of the several possibilities offered by modeFRONTIER to validate the meta-models.

4. Another important step is the assessment of the meta-model which involves evaluating the performance of the models, as well as the choice of an appropriate validation strategy. In modeFRONTIER, the engineers have several charts and statistical tools at their disposal for evaluating the goodness of the meta-models [Fig. 3]. Gaining insight from the meta-model and its error permits the identification of important design variables and their effects on responses. This is necessary to understand the behavior of the model, to improve it or to redefine the region of interest in the design space.

5. The last step consists of the use of meta-models to predict responses at untried inputs and performing optimization runs, trade-off studies, or further exploring the design space. As these points are extracted from meta-models and not obtained through real simulations, they are considered virtual designs. Even this last step is quite an easy task in modeFRONTIER; the user can immediately re-use the generated meta-models to speed up the optimization.

Meta-models for laboratories

The previous section describes how meta-models can help to speed up optimization by substituting time consuming simulation models. A similar approach can be used to create synthetic models from experimental data.

In this case, the aim is to substitute a time consuming and probably costly

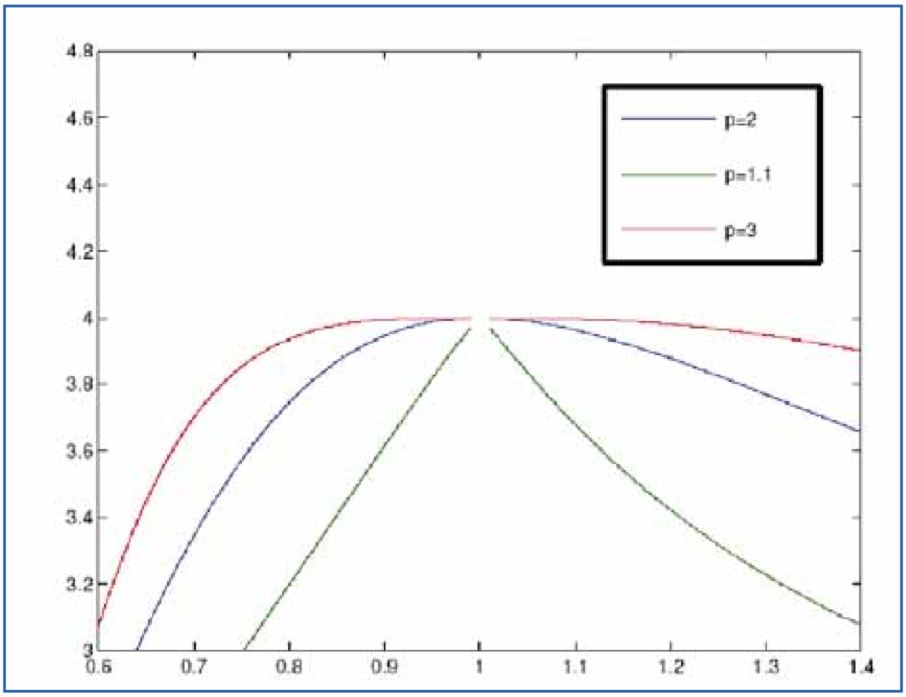

Figure 4: The effect of choosing different values of the characteristic exponent p in the weighting function around a point of the training dataset. The function flattens as long as the exponent grows.

experiment with a good enough mathematical model.

modeFRONTIER is able to import many file formats (XLS, TXT, CSV…), within a few easy steps. These designs resulting from experiments can be used to carry out statistical studies, such as sensitivity analysis, training for response surface modeling exactly as described in the previous sections.

In modeFRONTIER, all the tools for measuring the quality of meta-models in terms of statistical reliability are available. Moreover, modeFRONTIER gives a set of reasonable meta-modeling methods to interpolate different kinds of data. These methods include:

- Multivariate Polynomial Interpolation based on Singular Value Decomposition (SVD)
- K-Nearest, Shepard method and its generalizations. Shepard's method is a statistical interpolator which works through averaging the known values of the target function. The weights are assigned according to the reciprocal of the mutual distances between the target point and the training dataset points. The k–nearest method averages only on the most k nearest data to the target point. Shepard's method is one of the so called Point Schemes, i.e., interpolation methods which are not based on a tessellation of the underlying domain. Shepard is maybe the best known method among all scattered data interpolants in an arbitrary number of variables in which the interpolant assumes exactly the values of the data. The interpolated values are always constrained between the maximum and the minimum values of the points in the dataset. The response surface obtained with this method has a rather rough and coarse aspect, especially for small values of the exponent. Perhaps one of the most relevant drawbacks of this method is the lowering of maxima and the rising of minima. In fact, one usually expects that averaging methods like Shepard's flatten out

extreme points. This property is particularly undesirable in the situation shown in Figure 4, where the interpolating model disastrously fails to describe the underlying function, which is an ordinary parabola. It is self–evident that this feature is crucial for seeking the extremes.

- Kriging: Kriging is a regression methodology that originated from the extensive work of Professor Daniel Krige, from the Witwatersrand University of South Africa, and especially from problems of gold extraction. The formalization and dissemination of this methodology, now universally employed in all branches of geostatistics, as oil extraction and idrology among others, is due to Professor Georges Matheron, who indicated the Krige's regression technique as krigeage. This is the reason why the pronunciation of kriging with a soft "g" seems to be the more correct one, despite the hard "g" pronunciation mainly diffused in the U.S. Thanks to the support of the Department of Mathematical Methods and Models for Scientific Applications of the University of Padova, modeFRONTIER contains a simple kriging featuring the four variogram models with the possibility of auto determination of the best fitting of the experimental variogram. The fitting procedure uses Levenberg–Marquardt to minimize the sum of the squares of the differences between values from the experimental variogram and values from the model. Moreover, the user is warned when the best fitting variogram shows some clue of unacceptability, or still larger than the larger differences between values in the dataset.

- Parametric Surfaces: Useful whenever the mathematical expression of the response is known, except for some unknown parameters. The training algorithm calculates the values of the unknown parameters that yield the best fit.

- Gaussian Processes: Implement the Bayesian approach to regression problems: The knowledge of the response is expressed in terms of probability distributions. This algorithm is best suited for non polynomial responses.

- Artificial Neural Networks: As well as many human inventions or technical devices, artificial Neural Networks take inspiration from Nature in order to realize a kind of calculator completely different from the classical Von Neumann machine, trying to implement at the same time the hardest features and tasks of computation as parallel computing, nonlinearity, adaptivity and self training. A neural network is a machine that is designed to model the way in which the brain performs a particular task or function of interest. To achieve their aims, neural networks massively employ mutual interconnections between simple computing cells usually called neurons. Networks simulate the brain in two aspects: The knowledge is acquired through a learning process and the information is stored in the synaptic weights, i.e., the strengths of the interconnections between neurons [Fig. 5]. The class of Neural Networks included in modeFRONTIER with a single hidden layer is shown to be capable to interpolate any functions with minimum request of regularity.

- Radial Basis Functions (available from version 4.0)

The description of each interpolation method constitutes by itself a separate topic and paper, hence going deeply into this kind of description is not the aim of this article.

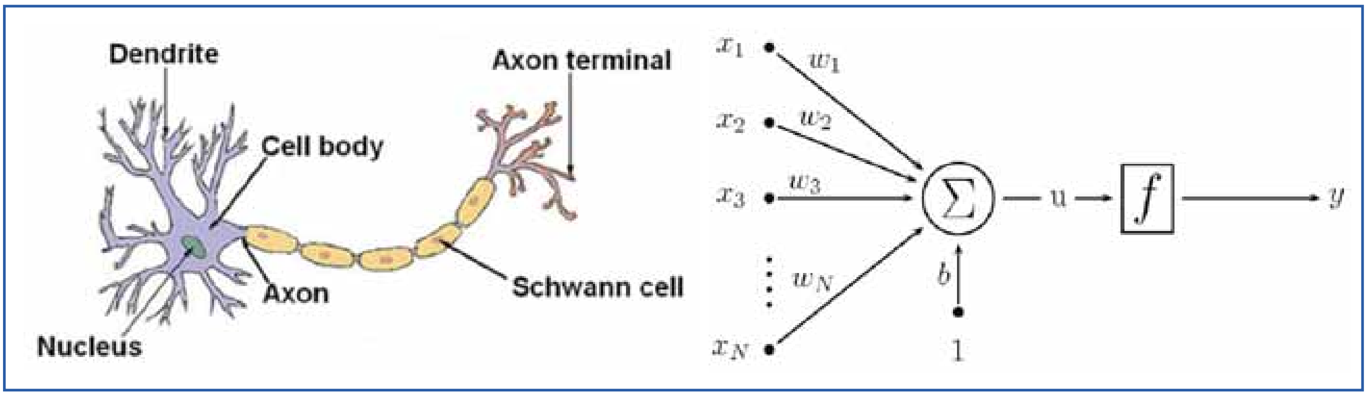

Figure 5: Neural Networks (NN) are inspired by the functioning of biological nervous systems. A real neuron (left) and an artificial neuron (right)

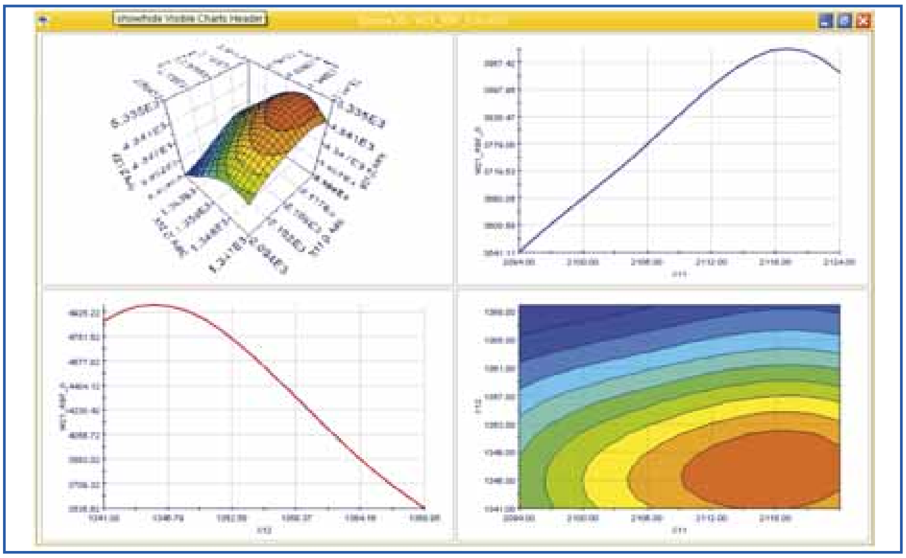

Figure 5: modeFRONTIER tool for meta-models 3D-exploration

Considering that several methods for interpolation are available, both in modeFRONTIER and in literature, an engineer may ask which is the best model to be used. There is an obvious notion that more simple functions can be approximated better and more complex functions are in general more difficult to approximate regardless of the meta-modeling type, design type and design size. A general recommendation is to use simple meta-models first (such as on low order polynomials). Kriging, Gaussian and Neural Network should be used for more complex responses. In general and regardless of the meta-model type, design type, or the complexity of the response, the performance tends to improve with the size of the design, especially for Kriging and Artificial Neural Networks.

Validation of Meta-models

modeFRONTIER has a powerful tool for the creation of meta-models, as it gives the possibility to verify the accuracy of a particular meta-model and to decide whether or not to improve its fidelity by adding additional simulation results to the database. It is possible to decide on effective surfaces for statistical analysis, for exploring candidate designs and for the use as surrogates in optimization. If the training points are not carefully chosen, the fitted model can be really poor and influence the final results. Inadequate approximations may lead to suboptimal designs or inefficient searches for optimal solutions.

That is why validation is a fundamental part of the modeling process. In modeFRONTIER, during the interpolation, a list of messages and errors generated by the algorithms is shown. The messages provide suggestions for a better tuning of the selected models. They generally list the maximum absolute error which is a measure that provides information about extreme performances of the model. The mean absolute error is the sum of the absolute errors divided by the number of data points, and is measured in the same units as the original data. The maximum absolute percent error is the maximum absolute numerical difference divided by the true value. The percentage error is this ratio expressed as a percent. The maximum absolute percent error provides a practical account of the error, measuring by what percentage a data point deviates from the mean error. There are many other measures that might be used for assessing the performance of a meta-model (e.g. the R-squared).

Conclusions

Both websites, www.esteco.com as well as www.network.modefrontier.eu, the portal of the European modeFRONTIER Network, provide several examples of how to use meta-modeling techniques to speed-up optimization.

For any questions on this article or to request further examples or information, please email the author:

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modeFRONTIER as a Statistical Tool

Nowadays, the fact that the use of statistical software can improve processes or drive and speed up the development of new products is well-known. The aim of this article is to show that modeFRONTIER can be considered as a complete and comprehensive software for data analysis able to perform a statistical consideration of database.

The Designs Space in modeFRONTIER version 4 can be considered as a stand-alone environment, where the user is able to perform extensive and complete statistical analyses of data deriving from different contexts. The statistical environment in modeFRONTIER 4 should be considered as a compelling tool for the decision-making process.

In its new version, modeFRONTIER offers a brand new environment which provides a wide variety of tools, reports and charts that can be used to explore data and perform complex statistical or engineering analyses.

For example, the user can easily:

- Visualize data using several charts such as the scatter plot or bubble charts. The bubble chart is a variation of the scatter chart, where the data points are replaced by bubbles. The bubbles provide a way for displaying a third variable in the two dimensional chart. The diameter of each bubble is proportional to the value it represents: the larger the bubble, the greater the value.
- Monitor trends and time series by means of the history plots with its moving average and Bollinger bounds;
- Visualize data distributions by using histograms, probability and cumulative distribution plots;
- Find out important linear relations between variables using tools that summarize all these effects in a single chart, such as the correlation chart and the scatter matrix;
- Find series outliers by means of useful charts such as Box-Whiskers or Quantile-Quantile (Q-Q) plot;
- Verify whether or not a series of data corresponds to a given distribution using the distribution fitting, the histogram plot and the Q-Q plot;
- Check the effects of the parameters on the outcomes using useful statistical tools such as the DOE main effect or the interaction effects;
- Perform several statistical tests (e.g. t-Student analysis, ANOVA).

In the post-processing panel, a complete new environment named Multivariate Analysis (MVA) includes tools that provide users with the possibility to:

- Organize designs into groups according to a given rule and look for clusters of data (hierarchical and partitive clustering);
- Build Self Organizing Maps (SOMs) in order to have an easy-to-read bi-dimensional representation of complex multi-dimensional data.

Moreover, and as in the previous version, the user can also take advantage of the Response Surface Methodology (RSM), which allows the construction of meta-models of data and eventually to perform virtual optimizations. This capability has particularly been improved as part of a painstaking research in the upcoming release.

It is quite straightforward to understand that it is very difficult, nearly impossible, to effectively analyze and summarize a huge amount of data without the help of a good statistical analysis tool. The following example demonstrates that modeFRONTIER can be considered as a complete tool for making statistical analysis of complex multidimensional data.

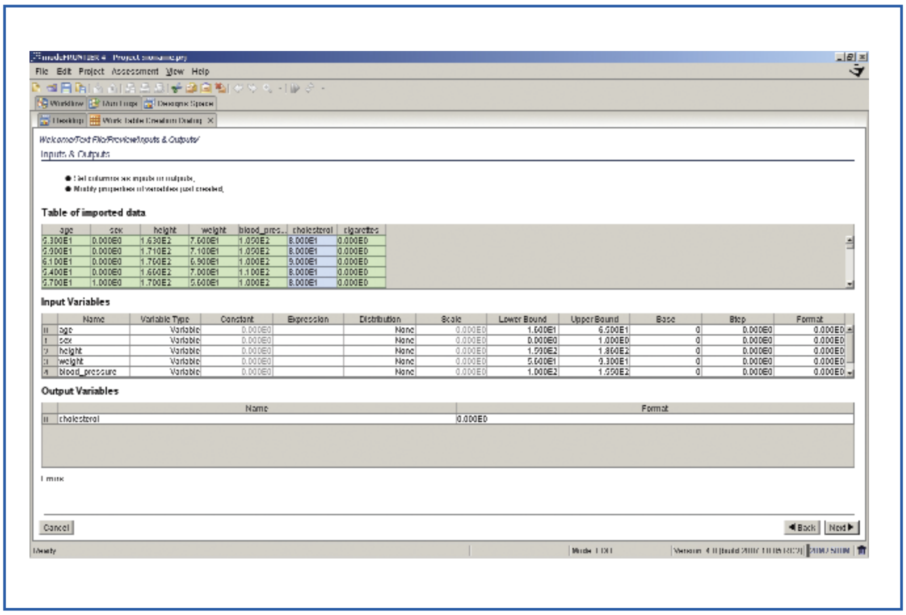

Figure 1: one step of the Data Wizard. The tool for importing data into modeFRONTIER

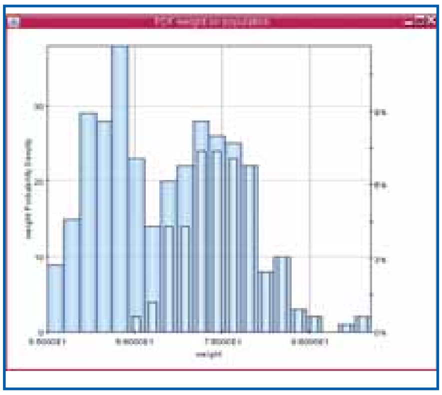

Figure 2: This histogram chart shows that the population weight has a distribution with two distinct peaks. This is due to the overlapping of two distinct Gaussian distributions for men and women.

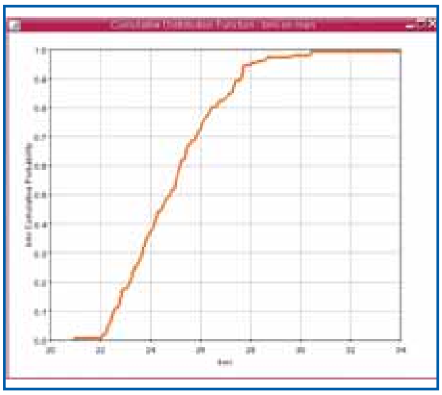

Figure 3: modeFRONTIER chart showing the ECDF of the population BMI.

Example – Evaluate the risks of LDL cholesterol

In order to show how the statistical instruments included in modeFRONTIER can be used to extract the most relevant information from a database, we present the following simple example.

Let us suppose that we have collected the sex, the age, the height, the weight, the number of cigarettes smoked per day and the systolic blood pressure of a certain group of people and, finally, their level of LDL cholesterol. These data could be the result of a medical investigation which, obviously, could also consider many other aspects of patient health, including for example the consumption of alcohol, the triglycerides level and so on. All the selected quantities aim at monitoring some of the main risk factors of cardiovascular diseases. The data contained in the database have been generated artificially and for demonstration purposes only, taking into account the information contained in [1] and [2].

All these data can be easily collected in a table whose dimension can be obviously very large, depending on the number of monitored people.

Load data in modeFRONTIER and manage work tables

We can suppose that this kind of data is usually well-organized in a file, where columns collect the age (in [years]), the sex (0 for men, 1 for women), the height (in [cm]), the weight (in [kg]), the blood pressure (in [mm hg]), the LDL cholesterol level (in [mg/dl]) and finally the number of cigarettes smoked per day.

By means of the Data Import Wizard [Figure 1], it is very easy to load the data into modeFRONTIER. During the import phase, the user can remove rows and columns containing useless data, specify the role of each column, insert objectives and constraints if any and set up the visualization format for numbers.

In this example, the variable "cholesterol" is set as output while all the others are set as inputs. Moreover, thanks to the work table capabilities, it is also possible to insert additional columns containing derived data. In this example, we can introduce the ratio between the weight (in [kg]) and the squared height (in [m]). This ratio is commonly named as body mass index (BMI) and it is often used to identify if a person is of normal weight or not.

With the Find tool, it is easy to select designs which satisfy certain conditions (e.g. age less than a given value and weight greater than a specified limit) and thus to subdivide designs into categories or create new tables of data. For example, the BMI values usually considered normal lay between 18.5 and 25.0, hence one can easily determine if a patient's BMI exceeds or falls below this range.

Histograms

Once the data have been loaded, it is straightforward to build the histograms charts by changing the number of classes in order to fit the user's needs. The probability density functions which better fit the data are highlighted, and the user can visualize them superimposed on top of the histogram. As it can be seen in example [Figure 2], the population weight has a distribution with two distinct peaks. If one marks the designs corresponding to the men (sex = = 0), the designs are consequently highlighted in the histogram. In this way, it is easy to understand that, with reference to the variable weight, the population is substantially divided into two groups, men and women. A similar consideration can be done if the variable height is considered.

In the table below, the graph collects the most important statistics of the data (mean, standard deviation etc).

Obviously, the same operation can be performed by dividing data according to other criteria and consequently constructing subgroups of data which can be analyzed separately.

Cumulative distribution

The cumulative distribution plot gives indications on the probability that a given event arises in the population. It reports the experimental cumulative distribution (shortly referred to as ECDF)

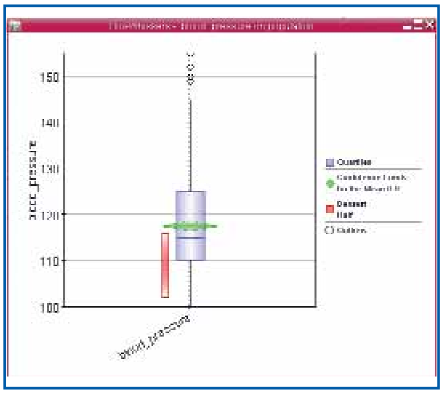

Figure 4: modeFRONTIER showing a box-whiskers chart of the blood pressure.

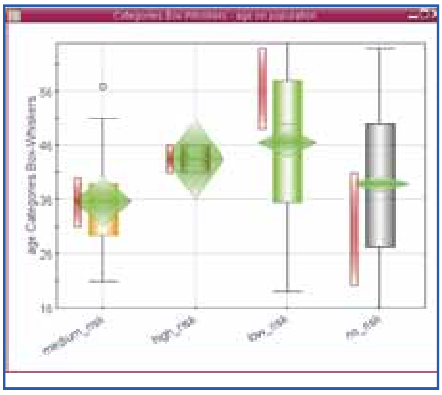

Figure 5: Box-whiskers showing four different categories of risk.

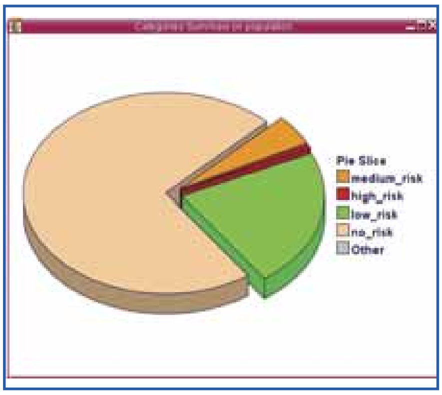

Figure 6: A pie plot describing the percentages for each category. It can be useful to have a global view on how the population is organized. In this case a large majority of the subjects do not present any risk (according to our own subdivision), while roughly 5% have a medium/high risk.

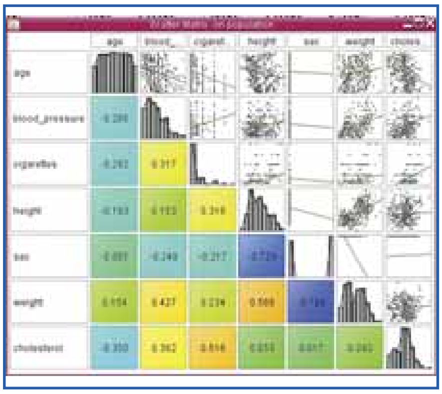

Figure 7: A scatter matrix summarizes a lot of information in a single chart. It helps in finding out linear relations between variables.

together with the most probable theoretical CDF, if any.

In this example [Figure 3], there is roughly a 50% probability to find a man who is overweight, being 0.5 the CDF value corresponding to a BMI of 25. Only a small portion (less than the 5%) of the male population is obese, having a BMI greater than 30.

Box-Whiskers

The Box-Whiskers plot can be used to visualize the distribution of data in an effective way, summarizing certain information about the data, such as the mean and its confidence interval, the quartiles and eventually the outliers. The confidence limit is an estimate for the mean with lower and upper limits. It gives an indication of how much uncertainty is in our estimate of the true mean. The narrower the interval, the more precise is our estimate. Confidence limits are expressed in terms of a confidence coefficient. Although the choice of confidence coefficient is somewhat arbitrary, in practice 90%, 95%, and 99% intervals are often used, with 95% being the most commonly used.

The last ones are the designs that fall out of an interval centered in the mean and with semi-amplitude of 1.5 of the standard deviation. In the example [Figure 4], it is interesting to note that, if we consider the blood pressure, there are four outliers which can be easily selected and eventually categorized.

The population can be categorized according to many criteria. In the following example, the most important risk factors for cardiovascular diseases have been considered. The patients have been organized into four groups, according to the risk level they belong to. The table summarizes the criteria adopted for the selection of the patients: obviously, this is only for demonstration purposes and has neither scientific nor medical relevance.

Now, it is possible to build a Category Box-Whiskers which plots the data series taking into account the subdivision into categories of the designs. In Figure 5, the population age is considered. It can be seen that, statistically, the most risky age for cardiovascular diseases ranges between 29.5 and 46 years (the first and the third quartiles of the medium and the high risk distributions have been considered respectively to define this range). However, if we examine also the low risk series, the age range should be enlarged up to 58. Moreover, it can be seen that the densest half is located in the highest part.

This means that the risk, even low, is statistically higher for increasing ages; this statement is corroborated by the fact that the densest half of the no risk distribution is located in the lower part.

Risk level	bmi		cigarettes		cholesterol		blood pressure
High	>30	and	>0	and	>130	and	>130
Medium	>22	and	>0	and	>100	and	>130
Low	>25			and	>100	or	>130
None	Otherwise						

Find out linear relations between variables

The Correlation matrix and the Scatter matrix are useful tools to check if there is any linear relation between variables. The correlation coefficient is a measure of the closeness of the linear relationship between two variables. The correlation coefficient is a pure number without units or dimensions which can

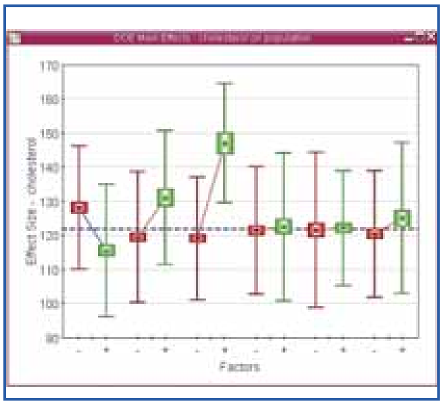

Figure 8: DOE Main Effects of the cholesterol level. This chart reveals that the consumption of tobacco and the blood pressure have a direct effect on the cholesterol level.

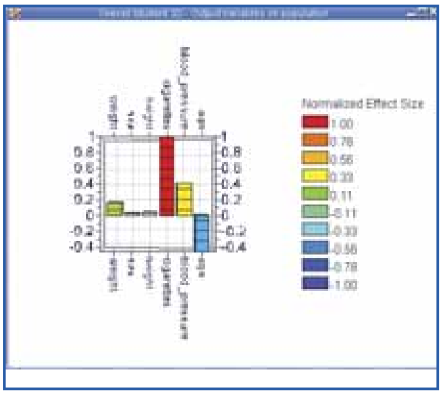

Figure 9: t-Student analyses on the output variables identifying the most important factors.

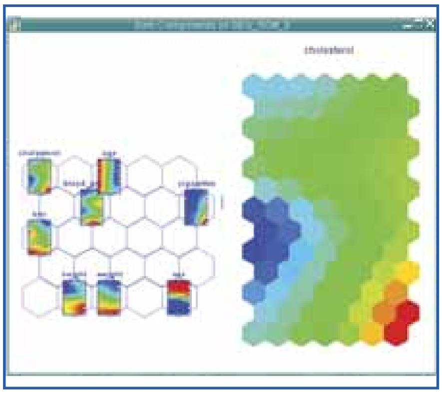

Figure 10: SOM components plot. This tool allows a global view of the database.

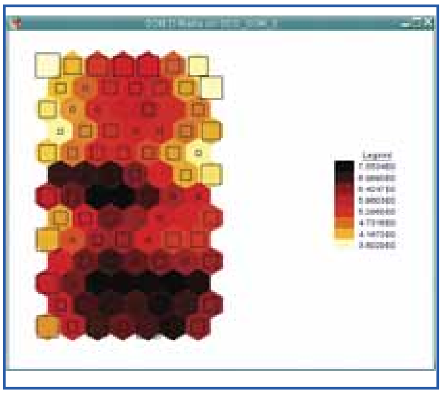

Figure 11: D-matrix of the SOM expressing the average distance between neurons

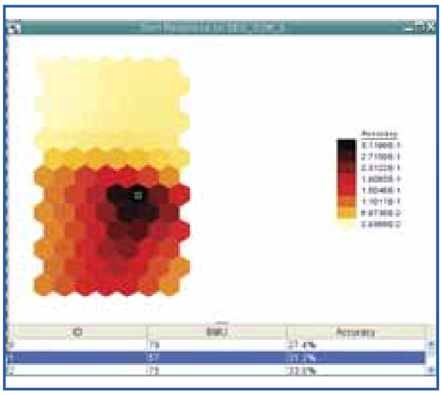

Figure 12: SOM response, this chart reports the best matching unit for each point. In this example, it allows the estimation of the cholesterol level of new patients.

range from -1.00 to +1.00. The value of -1.00 represents a perfect negative correlation while a value of +1.00 represents a perfect positive correlation. Positive values of the correlation indicate a tendency of the two variables to increase together. When the coefficient is negative, large values of the first variable are associated with small values of the second one.

The correlation ranking reports the most relevant connections. It is important to note that only relatively high values of correlation coefficients should be considered as reliable. In the Scatter matrix, the scatter plots together with the regression lines help to visualize the designs and understand how they are distributed in the space. All the graphs can be enlarged and explored by just clicking on their left-high corner.

In this example [Figure 7], it can be seen that the most important negative correlations involve the sex (-0.799) and the weight and the sex and the height (-0.728). The two most important positive relations involve the height and the weight (0.566) and the cholesterol and the number of cigarettes (0.516).

DOE main effects and Student Analysis

In the first place, for constructing a DOE main effect graph, it is necessary to identify effect and factors. The factor domains are split into two equal intervals containing the lowest and the highest values, identified with a – and a + respectively. In this way, two separate distributions are created and then plotted with respect to the chosen effect, using a layout very similar to the Box-Whiskers one. The resulting graph allows to identify the factors that influence the effect more and also to identify if there is a direct or inverse relation between factors and the effect.

In this case for example [Figure 8], the consumption of tobacco and the blood pressure have a direct effect on the cholesterol level, while the age and the height have an inverse effect.

By performing a t-Student analyses of data on the output variable, it is possible to understand which are the most important factors for the cholesterol levels. In the case of [Figure 9], it is quite clear that the high consumption of tobacco and high blood pressure are the two main factors which contribute to high levels of cholesterol.

The t-Student test is a very useful tool to identify the most important causes of an undesired effect. It may hence allow to make a correct diagnosis for a new patient just by looking at few parameters instead of the whole set.

Finally, it is interesting to point out that it is possible to generate a statistical report for every variable; this report represents a descriptive statistics tool that contains all the most important univariate statistics and graphs that completely characterize the data series. This report can even be saved in different formats, to allow the user to collect results and reuse them in a subsequent context.

The Multivariate Analysis (MVA) tool

In this example, the number of variables does not allow a compact visualization of designs. Actually, if the dimensionality is higher than 4 or 5 it becomes prohibitive, and somewhat useless, to plot all the information contained in the database using classical 2-dimensional charts. Obviously, this represents an important limit to the user's understanding of the data. For this reason, it is often extremely difficult to find groups of similar designs, identify outliers, and understand how the space is filled with designs. One possible strategy to solve this problem is to use a Self Organizing Map (SOM) which is

based on an unsupervised and competitive learning of a neural network. A SOM is able to map the designs, belonging to a multi-dimensional space, onto a lower dimensional space, preserving the original data topology and density.
SOMs are new important tools included in modeFRONTIER. They are part of the new multivariate analysis environment. Following step by step a user-friendly wizard, the creation of a SOM is really easy. For example, in this case, all variables can be considered to build the SOM except for the cholesterol and the BMI, as the latter one represents a derived quantity. The cholesterol and the BMI values can be seen as a kind of additional properties of the designs which do not contribute to the creation of the map.

When a self organizing map is created, a new table is added to the modeFRONTIER project collecting neurons of the map, the corresponding prototype vector and the designs which have been captured by the neuron itself. Different graphical ways are available to visualize results: the first one is surely the SOM components plot [Figure 10], where all the database components are displayed. This tool allows a global view of the database and supports the user in detecting if there is any relation between variables.

In this case for example, it is important to note that the cholesterol variable has a relatively smooth colored map, in view of the fact that this variable has been neglected during the map creation, this indicates that its behavior is related in some sense with the other components and not just a result of a random process. Actually, it can be seen that the maximum values of the cholesterol are located in the lower-left corner of the map, so are the cigarettes, the weight, the blood pressure and the height components. The age and the sex have similar maps, simply rotated, with well separated red and blue zones: this can be seen as a demonstration that the examined population represents females and males of all ages.

Other charts are available along with the SOM components. For example, the D-matrix expresses the average distance between a neuron and its neighborhoods. With this representation, it is possible to detect if there are clusters of data and to judge if eventually they are well separated or not. In the case of [Figure 11], it seems that there is no significant clustered distribution of data, the designs are uniformly spread on the map (the dimension of the square is proportional to the number of designs pertaining to a given neuron) especially in the brightest zones of the map, where the distances between designs are minimal.

Now, let us suppose that we have done another medical investigation on a second population, relatively homogeneous to the first one, collecting the same data of the first investigation, except for the cholesterol level. This time, the goal could be to understand how this second population is distributed and therefore, to predict the cholesterol level for all patients belonging to the second population. In this way, it is possible to identify dangerous situations, such as high values of cholesterol, without having any experimental evidence of such a fact.
To this aim, the user can load a new table of data in modeFRONTIER and plot a SOM response. This plot reports, for each new patient in the new table, the Best Matching Unit (BMU) of the SOM and affinity (that can be read as an accuracy value) between the value and the corresponding BMU. The BMU represents a kind of reference situation for the design under consideration, and therefore, the unknown cholesterol for the design can be taken from the corresponding neuron BMU.

Conclusions

In this article, the statistical and the multivariate analysis tools available in modeFRONTIER have been briefly presented. The aim was to demonstrate how all these tools can be used to capture the most important information contained in a database and how to discover hidden or not immediately evident relations between variables. The importance and usefulness of these tools have been presented by means of an example. In this example, the Self Organizing Map has been used with two different purposes; firstly as an effective representation of multidimensional data and, secondly, as a prediction tool.

References

[1] "Highlights on health in Italy 2004", by the WHO Regional Office for Europe, available at www.euro.who.int.
[2] "Health for All" data on the Italian population provided by ISTAT, the Italian Institute of Statistics, available at http://www.istat.it/sanita/Health

The websites www.esteco.com and www.network.modefrontier.eu, provide several examples of how modeFRONTIER can be used as a statistical tool.
For any questions on this article or to request further examples or information, please email the authors:

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Design of Experiments

"Design of experiments" was originated around 1920 by Ronald A. Fisher, a British scientist who studied and proposed a more systematic approach in order to maximize the knowledge gained from experimental data. Prior to this, the traditional approach was to test one factor at a time which meant that during the experimental phase, the first factor was moved while the other factors were held constant. Then the next factor was examined, and so on. By using this old technique, many evaluations were usually needed to get sufficient information which turned out to be a time-consuming process. The approach proposed by Ronald Fisher surpassed the traditional approaches as it considered all variables simultaneously, changed more than one variable at a time, thus getting the most relevant information with the minimal effort.

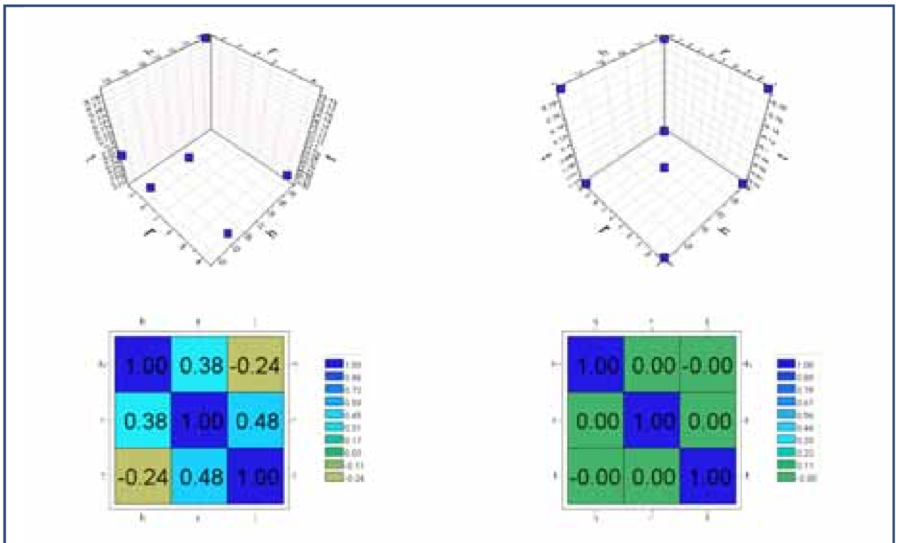
Maximizing the knowledge of experimental data

Since then, design of experiments has become an important methodology that maximizes the knowledge gained from experimental data by using a smart positioning of points in the space. This methodology provides a strong tool to design and analyse experiments; it eliminates redundant observations and reduces the time and resources to make experiments.

The intention of this article is to demonstrate particular features of modeFRONTIER that make design of experiments easy to be used and implemented. When using an optimization tool such as modeFRONTIER, there are at least four good reasons to apply "design of experiments" (DOE) from now on:

1) To get a good statistical understanding of the problem by identifying the sources of variation;
2) To provide points which can be used to create a meta-model by involving a smart exploration of the design space;
3) To provide a good starting point for an optimization algorithm, such as Simplex or Genetic Algorithm (GA);
4) To check for robust solution.

In general, we can say that a good distribution of points achieved through a DOE technique will extract as much information as possible from a system, based on as few data points as possible. Ideally, a set of points made with an appropriate DOE should have a good distribution of input parameter configurations. This equates to have a low correlation between inputs. The latter becomes obvious when we look at the left diagram in the figure below where a case with 3 input variables is shown. Clearly, if our combinations of inputs were all in the same part of the design space, the correlation between them would be high. However, we would be learning very little about the other parts of the input parameter space, and hence about those parts of the system. The right choice of DOE starts from the decision on the number of experiments. For example, when we consider the case of a statistical analysis where the cost of each experiment is 1000 $, we likely have two goals to pursue: to have a good set of samples and a cost-effective campaign of experiments. The problem is similar when the sample is not anymore an experiment to be executed in the laboratory but a numerical analysis instead. If we suppose, for example, that each point corresponds to a numerical analysis that lasts for one day or even more, which can be the case when using very heavy numerical tools such as PAMCrash, LS-DYNA or complex CFD analysis with million and millions of cells. Obviously, the calculation time will



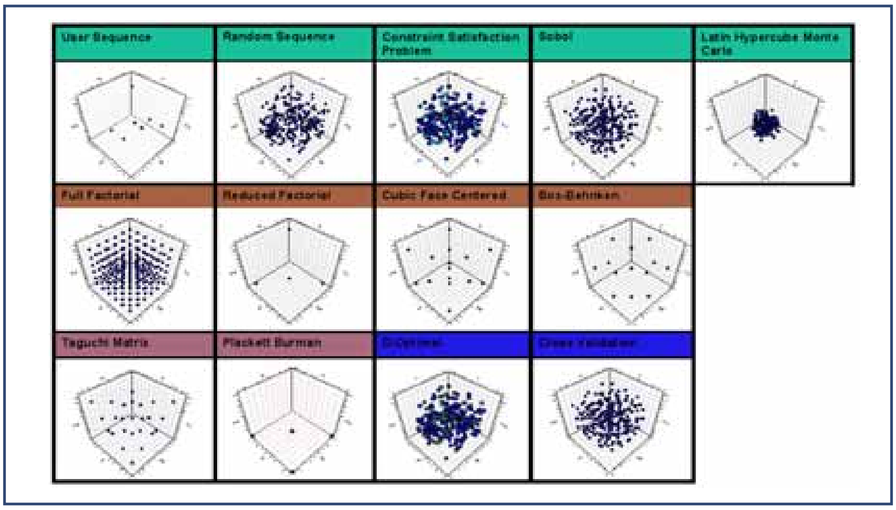
The variables are correlated
Bad distribution

The variables are NOT correlated
Good distribution

depend on the hardware available and the number of available licenses of the software used. The objective in this case is to have a good set of calculated designs in order to construct a meta-model to speed up the optimization by using a virtual solver. We need to use the tools available in modeFRONTIER to check the (non-) linearity of the system. If we think that we have obtained a reliable meta-model, we can use that for "virtual" optimization purposes. In other words, we can use the meta-model to obtain the best result(s). Of course, this always needs to be followed by a careful validation: the combination of inputs which created any virtual optimum should be fed back into the analysis to verify the "real" result. Anyhow, the situation is quite similar with the only difference that in this case the DOE technique reduces the time instead of the cost of the experiments.

This article aims at stressing the fact that, before employing a search strategy, it may be useful or even essential to carry out a preliminary exploration of the design space. This might be in order to provide an initial population of candidate designs or to let the user build some understanding of the behavior of the objectives and constraints, prior to deciding what further search method to use. For this purpose, a range of reasonable ways exists for positioning a set of N points in the space of designs. modeFRONTIER provides all the tools for measuring the quality of a DOE in terms of statistical reliability. Moreover, modeFRONTIER gives a set of reasonable DOE methods to tackle different kind of problems. These methods include:

1) User-chosen set: Based on the user's previous experience;
2) Exploration DOEs, useful for getting information about the problem. These methods eliminate subjective bias and allow good sampling of a configuration space. Exploration DOEs can serve as the starting point for a subsequent optimization process, or as a database for response surface training, or for checking the response sensitivity of a candidate solution. (Random Sequence, Sobol, Latin Hypercube, Monte Carlo, Cross-Validation)
3) Factorial DOEs, a large family of techniques essential to perform good statistical analyses of the problem, to study main and higher-order interactions between variables (Full and Reduced Factorial, Cubic Face Centered, Box-Behnken and Latin Square).
4) Orthogonal DOEs, useful if the purpose is to identify the main effects and all the interactions are negligible or in order to control noise factors (Taguchi Matrix, Plackett Burman).
5) Special Purposes DOEs, suitable for particular tasks to be achieved in design planning and whenever other methods do not fit. (D-Optimal, Constraint Satisfaction Problem)

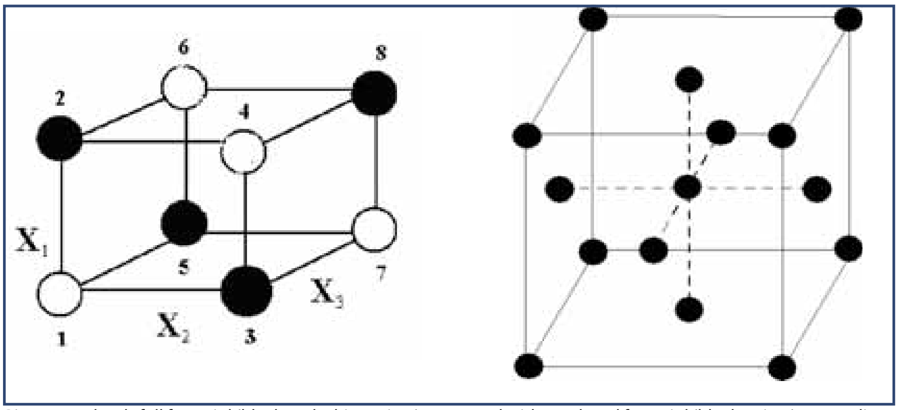


In the picture below a sub-set of 3-dimensional DOEs is shown. It is clear that some are very structured, such as the Full Factorial or Latin Square, while others show more a cloud of points, such as Sobol and Random Sequence. The choice of technique depends very much on the number of calculations which can be performed and on the kind of investigation that should be done.

DOE for statistical analysis

The original use of DOE planned by Fisher refers to methods used to obtain the most relevant qualitative information from a database of experiments by making the smallest possible number of experiments. Fisher proposed a new method for conducting experiments, eliminating redundant observations, reducing the number of tests in order to provide information on the major interactions between the variables.

The DOE approach is important to determine the behavior of the objective function we are examining because it is able to identify which factors are more important. The choice of DOE depends mainly on the type of objectives and on the number of variables involved. Usually, only linear or quadratic relations are detected. However and fortunately, higher-order interactions are rarely important and for most purposes it is only necessary to evaluate the main effects of each variable. This can be done with just a fraction of the runs, using only a "high" and "low" setting for each



Picture 1: 2-levels full factorial (black and white points) compared with a reduced factorial (black points) on a 3-dimensional space [left]. Cubic face centered on a 3-dimensional space, this method is equivalent to a full factorial with two levels plus the mid-points of the design space hypercube [right].

factor and some central points when necessary. For example, reduced (or fractional) factorial attempts to provide a reasonable coverage of the experimental space while requiring significantly fewer experiments. In using reduced factorial designs, we do not create designs at all possible level combinations, but only at a fraction of them. The figure above represents an example of a reduced factorial DOE on a 3-dimensional space. The set of black points represents a reduced factorial and is composed by exactly half the number of the total points. Anyhow, using this DOE, the information related to the binary interaction between variables is kept and main effects are still visible. Hence, it is possible to use a fractional factorial plan to understand the most important characteristics of the problem at hand faster.

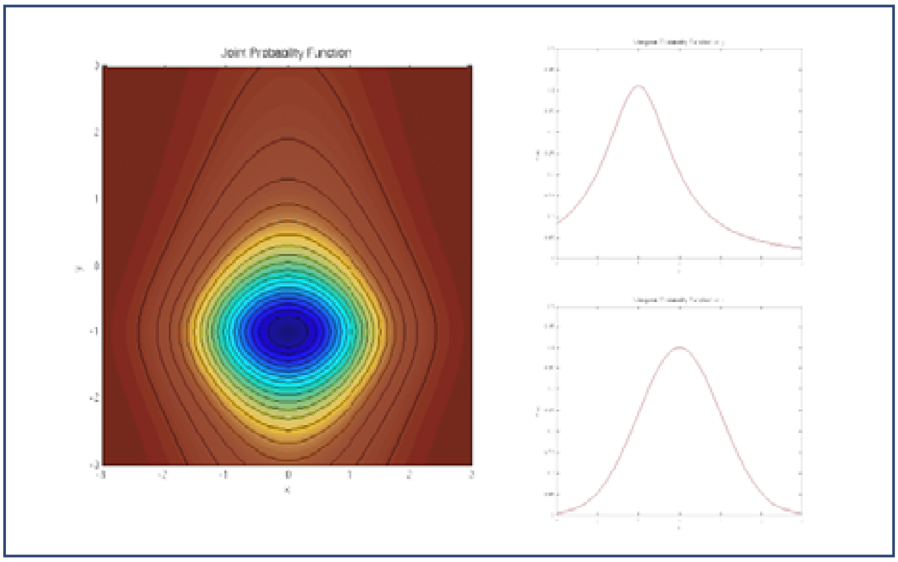
There are several different design of experiment techniques available: Reduced factorial, Plackett-Burman, Box-Behnken, cubic face centered, just to mention a few. These kinds of DOEs are useful to determine the most important design variables, and to research the most favorable region for the objective functions. Hence whenever DOE is used during the optimization process, it should always be applied before the actual optimization phase as it can be useful to identify the main effects, to reduce the number of variables and/or to shrink the range of variations.

Several statistical tools make modeFRONTIER a powerful instrument to analyse experimental data: main effects plots, correlation matrix, student charts and many other. All these tools guide the user to the real essence of the problem in hand.

DOE for robustness

The presence of uncertainty makes the traditional approaches for design optimization especially insufficient. Robust optimization and the related field of optimization under uncertainty are well known in economics. The importance of controlling variability as opposed to just optimizing the expected value is well recognized in portfolio management. In fact, when constructing a balanced bond portfolio one must deal with uncertainty in the future price of bonds. Robust optimization has recently started to gain attention within the engineering and scientific communities as many real world optimization problems in numerous disciplines and application areas, contain uncertainty. This uncertainty is due to errors in measuring, or difficulties in sampling, or moreover may depend on future events and effects that cannot be known with certainty (e.g. uncontrollable disturbances and forecasting errors).

In many engineering design problems, design parameters may only be known to some tolerance or in some cases, they may be described by a probability distribution. Moreover, designing a product for a specific environmental scenario does not guarantee good performance for other environments: there is a risk associated with the chosen design and in fact another design may have a lower risk.



Picture 2: This contour plot on the left shows a multivariate statistical distribution of two variables, x and y. Warmer colors indicate higher values for probability distribution: i.e. the region with a greater probability to generate points is the red peak. This probability distribution function of more than one variable is called joint probability function. The two charts on the right show the two marginal probabilities: in this particular example the probability function along x is a Normal distribution centered in 0 and with standard deviation equal to 1; the marginal probability function along the y is a Cauchy distribution centered in -1 and with scale factor equal to 1.

Deterministic approaches to optimization do not consider the impact of such variations, and as a result, a design solution may be very sensitive to these variations. These uncertainties should be included in the optimization procedures, so that prescribed robustness can be achieved in the optimal designs.

To select the best parameter set, we need an algorithm which explores the parameter space in an efficient way and chooses solutions that correspond not only to the best average but are also located on broad peaks or high flat regions of the function. Such requirements will ensure that small variations in the model parameters keep the system in the high performance region.
As the input variables are uncertain, these uncertainties can be approximated in terms of a probability density function. Probability density functions can be used to generate a series of sample points, which are used to evaluate the model and create a corresponding output probability density function. To specify the diverse nature of uncertainty, different distributions can be used. For example, a normal (or Gaussian) distribution reflects a symmetric probability of the parameter above and below the mean value. On the other hand, a uniform distribution represents an equal likelihood in the range of inputs. Other distributions, like the lognormal and the triangular, are skewed such that there is a higher probability of values on one side of the median than on the other.

One of the most used techniques for sampling from a probability distribution is the Monte Carlo sampling which is based on a pseudo-random generator used to approximate a uniform distribution with a specific mean and variance. The advantage of this method lies in the fact that the results can be treated by using classical statistical methods (statistical estimation and inference). Unfortunately, this widely used method does not consider constraints on input parameters and can result in large error bounds and variance. Other sampling methods have been studied in order to improve the computation efficiency of the sampling. An efficient sampling methodology is latin hypercube. This method uses an optimal design scheme for placing the m points on the n-dimensional hypercube. Using this method, the sample set is more representative of the population even for small sample size. Considering that the number of samples plays an important role in robust design optimization, it has been computed that this method can speed up design under uncertainty and is at least 3 to 100 times faster than Monte Carlo techniques. Both Monte Carlo and latin hypercube sampling are available in modeFRONTIER in order to enhance the research of robust solutions.

Conclusions

The website www.esteco.com contains several examples of how to use DOE techniques. Most of the examples are slanted towards applications in fluid dynamics but this only reflects some of the research interests of the original authors as DOE applications and the coupling of these techniques with modeFRONTIER is of much more diverse nature.

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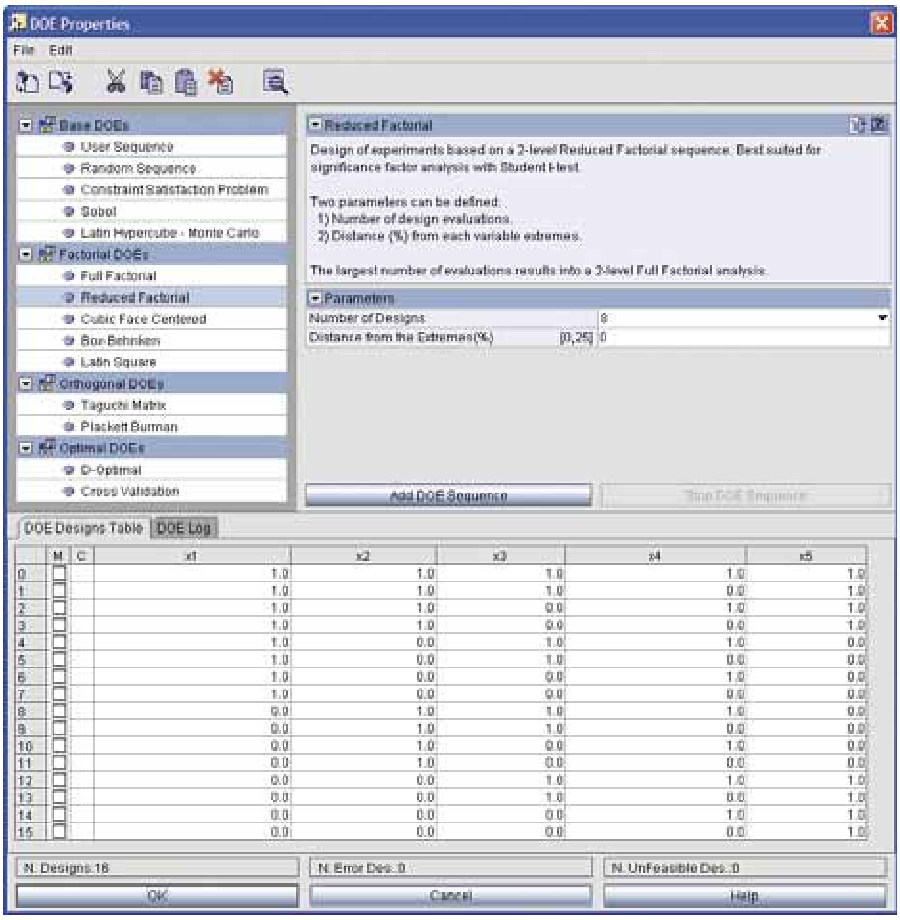


modeFRONTIER graphic user interface for Design of Experiments. The left part contains the list of available DOE algorithms that can be used to generate a proper set of points. The right panel is used to provide the parameters required by each DOE method.

Multi-body simulation and multi-objective optimization applied to Vehicle Dynamics

1. Introduction

Dynamical performances of two wheeled vehicles largely depend on the response of each component. Among all components, tires and suspensions are the most important sub-systems, because their role is to modulate any force going from the road to the chassis. Therefore, a deep knowledge of such parts, can be the turning key to develop better and safer motorcycles.
Multi-Body Simulation is the most suitable approach to perform vehicle dynamics investigation.

By creating parametric models, different configurations can be quickly evaluated, even at the earliest stage of the entire development process. From a business perspective, this means that wrong gateways can be dropped long before they lead to costly and useless real prototypes.

These benefits can be further increased by coupling the Multi-Body Simulation software with modeFRONTIER, which automatically plans and drives sets of simulations in order to perform complex tasks such as Design of Experiment, Parameter Sensitivity Analysis, and Multi-Objective Optimization.
This paper describes a demo application, where modeFRONTIER is asked to identify the parameters of a motorcycle front suspension to deliver more safety, more stability, and more riding comfort for a braking maneuver in straight running. Although the research is targeted to a very specific case, the proposed methodology can be straightforwardly extended to any user-defined running condition. Potentially, it is possible to build a single modeFRONTIER project to optimize different vehicle parts for various maneuvers.

As expected, results highlight that trade-off relationships connect the objectives, hence full optimization is almost impossible. Only 13, among the 1900 tested configurations, are able to simultaneously improve the 4 scalar indexes that have been previously defined to measure the objectives. Moreover, no design in this selection promises a decisive improvement of the stability. In order to meet these primary requirements, the best design is chosen accepting a slight reduction of stability. The decision task has been totally supported by the Multi Criteria Decision Making tool implemented in modeFRONTIER.

In-plane analysis of a Motorcycle Front Suspension

2. The 2D Motorcycle Model

The Motorcycle is a complex multi-body system and special efforts are necessary to reliably simulate the overall dynamics. The broad range of literature available on this topic covers all simulation fields, such as time domain behavior, optimal maneuver, steady trim, frequency response, modal properties, tire dynamics, and so on. Since this research aims at highlighting the benefits of implementing an optimizer into the simulation chain, a detailed and validated model is not available. Model features have been implemented following state-of-art guidelines to ensure sufficient result reliability.
As a simple test case, the vehicle behavior at braking during straight line motion is considered. In general, lateral dynamics plays an important role and a

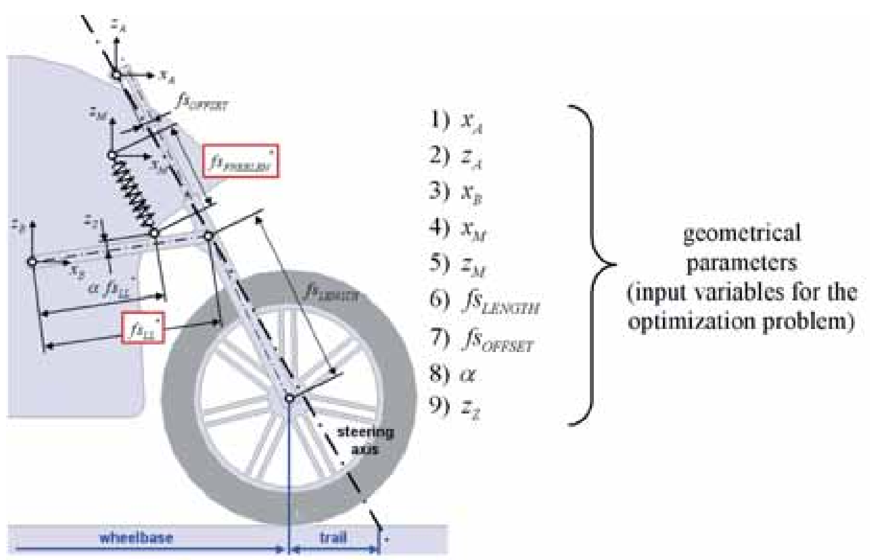


Figure 1 – Front Suspension layout and parameters

detailed 3D model would be recommended to perform thorough investigation. However, a 2D model includes enough features to study the influence of the front suspension on the braking distance, keeping the simulation complexity at reasonable level. Indirect considerations on stability and vehicle comfort can be made in any event by examining the variation of some in-plane quantities.

The motorcycle model used in this research consists of 7 rigid bodies, such as chassis (which includes the rider), rear wheel, swinging arm, front wheel and three bodies for the front suspension with telelever scheme. Bodies are connected using proper joints to obtain the exact number of in-plane degrees of freedom.

2.1. Front suspension

A special description is required for the fully parametric front suspension geometry (Figure 1). Parameters allow to change the position of “A”, “B”, and “M” pins with respect to the chassis. Also, front fork offset, lower fork length, and the main link characteristics are adjustable. Suspension geometry directly affects important vehicle dimensions such as wheelbase, mechanical trail, and center of gravity height. Wheelbase and center of mass position play a fundamental role in determining the vehicle braking

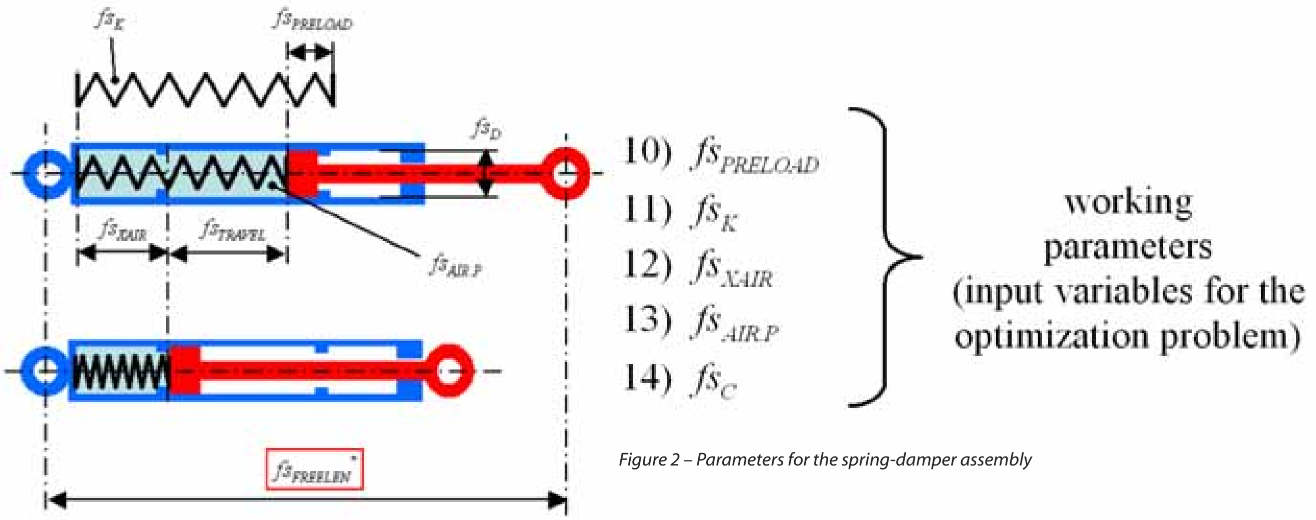
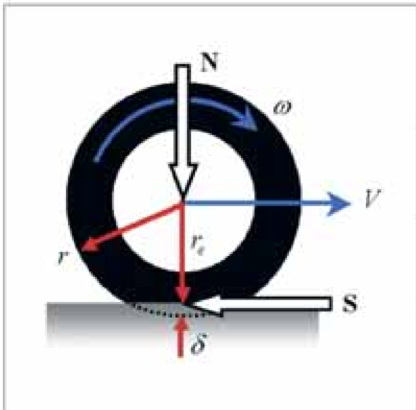


Figure 2 – Parameters for the spring-damper assembly



effective rolling radius	$r_e = r - \delta$
longitudinal slip	$\kappa = -\dfrac{\omega r_e - V}{V}$ $\begin{cases} \kappa = 1 \Rightarrow \text{wheel lock} \\ \kappa = 0 \Rightarrow \text{pure rolling} \end{cases}$
vertical load	$N = k_r \delta_r + c_r \dot{\delta}_r$
longitudinal force	$S = N D_x \sin(C_x \arctan\{B_x \kappa - E_x [B_x \kappa - \arctan(B_x \kappa)]\})$

Figure 3 – Tire longitudinal behavior

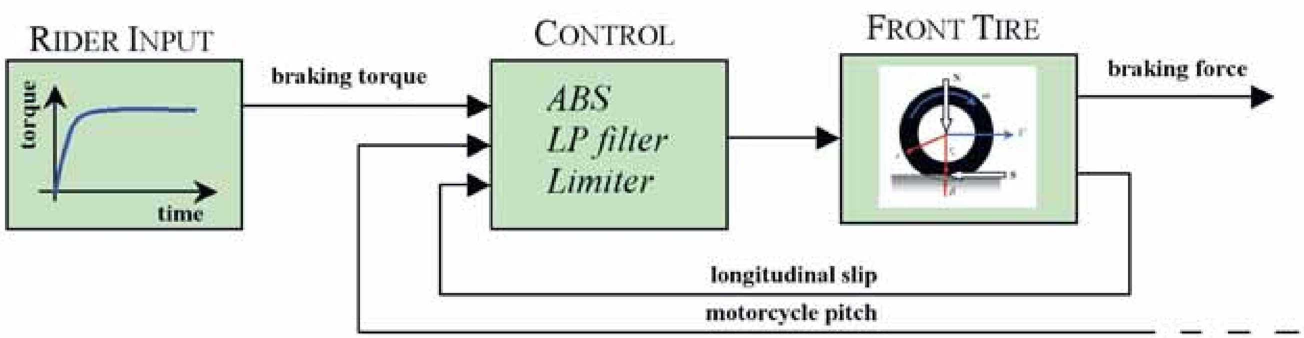


Figure 4 – Braking control

response. Since this research only aims at studying the suspension effects on the braking response, some tricks are used to make the above quantities almost independent from the general parameter assignment.

The spring-damper assembly (Figure 2) is also included in the parameterization. The overall force is obtained by combining the action of a linear spring and a pressurized air piston.

OUT	QUANTITY	FIELD	PRIORITY	BASELINE	OBJECTIVE	GOAL
y_1	trail variation	stability	2	–7.4 mm	increase	$y_1 > -7.4$ mm
y_2	wheelbase variation	stability	3	–5.1 mm	increase	$y_2 > -5.1$ mm
y_3	stopping distance	safety	1	81.7 m	reduce	$y_3 < 81.7$ m
y_4	pitch angle variation	comfort	4	3.7 deg	reduce	$y_4 < 3.7$ deg

Table 1 – Optimization Strategy

The working travel is governed by two high stiff end-stroke pads. Initial preload is obtained by assigning a non-zero air pressure and by imposing a partial compression of the spring. The linear damper has different coefficients for the elongation and compression phases. The free length of the assembly is calculated in order to keep the center of mass height constant when performing the static assembly.

2.2. Tires

Tires are modeled to accurately describe the generation of the longitudinal force. In accordance with Pacejka's formula, the longitudinal force S is a non-linear function of the longitudinal slip and a linear function of the vertical load. The Dx coefficient controls the maximum force that the tire can generate (adherence factor), whereas the others govern the shape of the force function. Maximum occurs for low slip ratio, whereas high slip leads to tire saturation and smaller forces. The tire model implemented here does not take into account any delay between slip and force raising.

2.3. Braking control

The simulation reproduces a typical emergency situation where the front brake is activated to stop the motorcycle from straight running at 130 km/h. The front brake simply reduces the angular speed of the front wheel, increasing the longitudinal slip that modulates the longitudinal braking force. During the entire maneuver, the vertical load is transferred from rear to front tire, proportionally to the deceleration. This means that the front tire becomes capable of generating a greater braking force. Braking dynamics are governed by two practical limits. In case of good adherence, the front braking force can become high enough to cause the lift of the rear wheel (stoppie condition). On the contrary, with small values of the Dx coefficients, the front tire reaches its saturation point and the front wheel locks.

The planned optimization makes sense if a control system (Figure 4) instantaneously calculates the braking torque that leads to the maximum braking force, with no rear wheel lift. This will fully exploit the motorcycle's braking capabilities. If any suspension update (design generation) affects these capabilities, the simulation will be able to capture such effect.

3. Optimization problem and objectives

The suspension characteristics influence both the way the braking force is generated (transient phase) and its value in steady condition (constant deceleration phase). It is expected that by changing the suspension parameters, it will be possible to obtain a higher force at a shorter interval, and hence a reduction of the total stopping distance. This is the most important

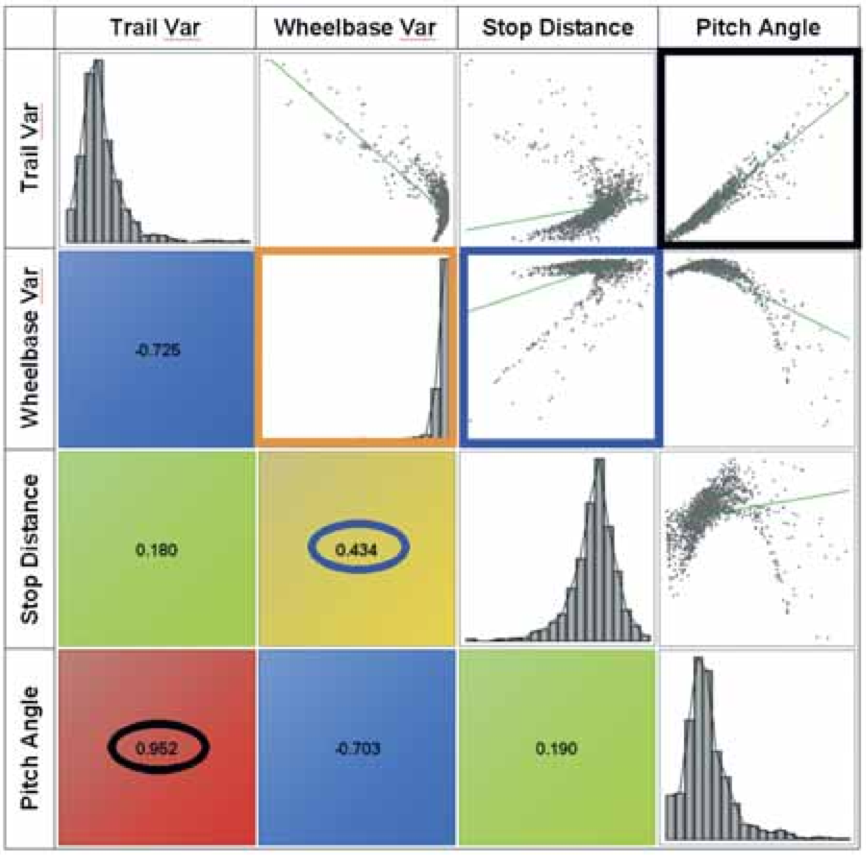


Figure 5 – Correlation matrix for the objectives

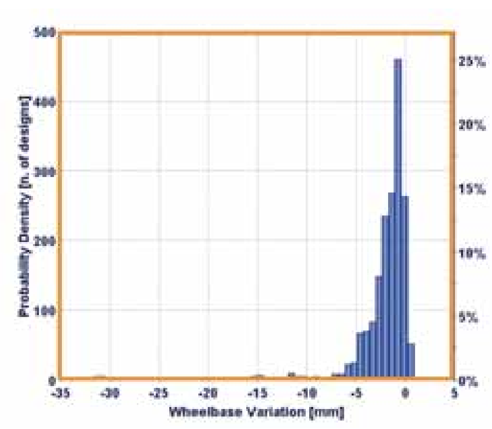


Figure 6 – Probabilità density function for wheelbase reduction objective

objective for the optimization problem. During the braking maneuver, both the wheelbase and the trail tend to get shorter, usually causing a reduction of the lateral vehicle stability. These phenomena can be limited by choosing an opportune suspension layout. Therefore, two objectives corresponding to trail and wheelbase shortenings are defined.

A further consequence of any braking action is the pitching forward of the motorcycle. This is not necessarily a problem, but excessive pitching might disturb the rider. For this reason, we ask the optimizer to identify designs that also limit the pitching.
All of the optimization objectives are listed in table 1, which includes also the performances given by the baseline motorcycle (i.e. initial design):

4. Software implementation

The parametric motorcycle model has been developed using a commercial multi-body software. Geometrical properties for the initial design have been indirectly measured from digital pictures, whereas inertial properties have been estimated. Control routines have been written in FORTRAN code and then linked to the main model. VISUAL BASIC modules have also been written to automatically export time domain results at the end of each simulation.

The workflow is fully defined in the modeFRONTIER environment, which controls any task and, most importantly, drives the optimization using its internal algorithms. The optimization philosophy is to explore the design domain (14 dimensional space) looking for the configurations that improve the system behavior in accordance with the 4 objectives. First, a DOE population with 112 designs is generated to map how the 4 objectives depend on the 14 input variables. Then, the Multi-Objective Genetic Algorithm of modeFRONTIER generates populations of new designs, using the information gained from previous runs.
To test each configuration and extract the corresponding outputs, modeFRONTIER executes internal operations and launches external applications. Here is the sequence of the main tasks:

- generation of an input variable set (DOE or MOGA algorithms);
- assembly of the motorcycle model (static multi-body simulation);
- calculation of any intermediate variables (external spreadsheet);
- braking simulation (time domain multi-body simulation);
- calculation of scalar indexes that describe the 4 objectives (external spreadsheet).

The entire project has tested the behavior of 1904 different suspensions (17 MOGA generations). Each design took about 2.5 minutes, hence total CPU time was 80 hours.

5. Optimization results

modeFRONTIER stores input variables, derived variables and output variables in a design table, whose rows reflect the tested configurations. Such a table is then processed to extract key information about the optimization scenario.

Main statistical relationships between variables (input-input, input-output, and output-output) may be investigated by plotting the correlation matrix. The example proposed in Figure 5 has been created to check for possible links between the 4 optimization objectives. The bottom-left section of the matrix shows the correlation factors, which provide a statistical measure of the linear association between objectives. Null, or small correlation indexes mean that there is no clear trend between the variables, whereas value +1 or close to +1 (or –1) indicate good direct (or inverse) correlation.

There are clear negative correlations between trail variation and wheelbase variation, as well as between pitch

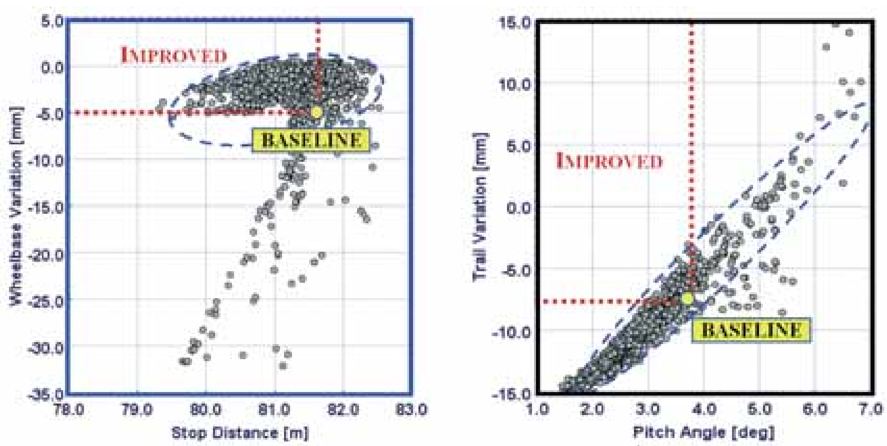


Figure 7 – Design evaluation

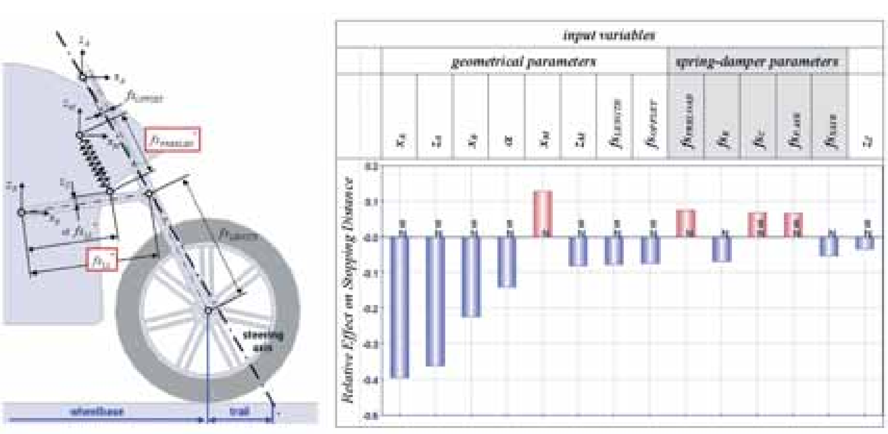


Figure 8 – Student chart: Effects of design parameters on stopping distance

the first step towards a simplification of the problem.

As an example, Figure 8 shows the t-Student chart for the stopping distance objective. The input parameters are listed from left to right, according to their effect on the chosen objective. The chart highlights that spring-damper characteristics are less important than parameters defining suspension geometry. The strongest (inverse) effect is given by coordinates of pin “A”, which means that moving backward and downward such joint will determine the reduction of the stopping distance.

angle and wheelbase variation. Statistically, this means that when the wheelbase shortening is small, both trail shortening and pitch angle tend to be more pronounced.

Diagonal cells illustrate the Probability Density Function Chart for each objective. They allow the identification of trends that may not be obvious. For example, the wheelbase variation distribution is strongly asymmetric, with higher probability density on the right side of the total range, from –65.0 mm to +0.8 mm. Since the optimizator was asked to limit the wheelbase shortening, the result is very satisfactory: more than 95% of motorcycles exhibit a wheelbase reduction between –5.0 mm and 0.0 mm (Figure 6). Other objectives are characterized by wider distributions, with less strong trends.

The upper-right section of the correlation matrix contains scatter charts, which represent the design distribution on 2D cartesian graphs having X&Y axes in accordance with row & column of the matrix. Two of these charts are highlighted and zoomed in Figure 7, for a better understanding. The left plot shows the connection between stopping distance and wheelbase. Design spots lie in a wide cloud, thus confirming a low correlation level (0.434). Trail variation and pitch angle, in contrast, are strongly correlated (0.952) as proved by the right plot, where design spots substantially lie on a narrow inclined area.

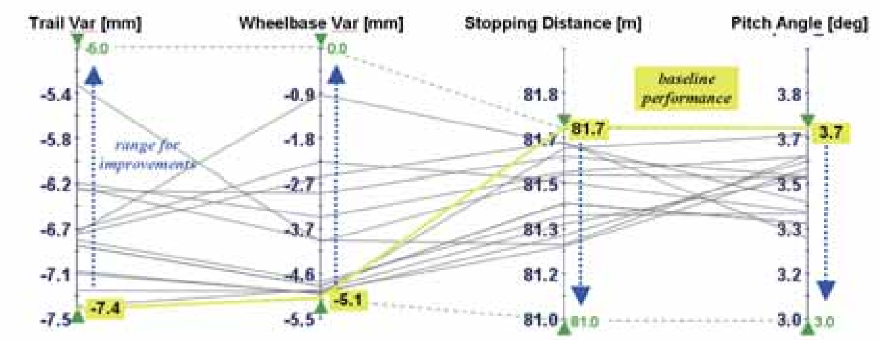


Figure 9 – Parallel chart to identify best designs

Besides examining object correlations, it is essential to analyze the relationships between objectives and input parameters. modeFRONTIER provides specific tools to rate the importance of each parameter, which is

6. Selecting the best design

In order to understand how effective the optimization has been, it is necessary to compare the designs, focusing on objective values. Figure 9 shows a parallel chart, where a graphical filter is used to hide all designs that do not meet one or more optimization goals (see last column of Table 1). Considering simultaneously the 4 optimization criteria, the 13 visible designs of Figure 9 are better than the baseline model. This selection is rather small (0.68 % of total), meaning that the baseline motorcycle was already well designed for the objectives we have chosen.

Theoretically the best design - among all - belongs to this sub-set. However, it can be observed that the only noticeable improvement concerns the

OUT	QUANTITY	BASELINE	DES. N. 566		DES. N. 792	
y_1	trail variation	–7.4 mm	-1.1 mm	-85 %	-15.2 mm	+105 %
y_2	wheelbase variation	–5.1 mm	-31.6 mm	+519 %	-3.8 mm	-25 %
y_3	stopping distance	81.7 m	79.6 m	-2.5 %	79.4 m	-2.8 %
y_4	pitch angle variation	3.7 deg	5.2 deg	+40 %	1.8 deg	-51 %

Table 2 – Best candidate performances; losses with respect to the baseline are highlighted in red color

wheelbase variation (from –5.1 mm to –0.9 mm). The gains for the other objectives, including the reduction of the stopping distance, are rather poor. To be fair, none of the 13 selected configurations improves the braking behavior sufficiently to justify a review of the baseline design.

Although at first glance it appears that the optimization failed, this may be a precipitate conclusion. In most cases, trade-off relationships exist between the objectives meaning that a slight loss in secondary ones opens a new scenario where the priority goal can be reached. modeFRONTIER includes a Multi Criteria Decision Making tool that uses pre-defined priorities to drive the choice in similar situations.

By applying such tool to the full design table, two “best” candidate designs have been selected; their performances are summarized in table 2.

Both solutions provide a significant reduction of the stopping distance which is an important step forward in terms of safety. Such positive results can only be reached provided that, in braking condition, either the shortening of the wheelbase (des. 566) or the shortening of the mechanical trail (des. 792) gets more pronounced with respect to the corresponding shortening measured on the baseline motorcycle. The first selected configuration (des. 566) also causes a slight increase in pitching motion.

To make a definitive choice, it is useful to compare both optimized motorcycles with the baseline model. Figure 10 clearly shows that design 566 does not differ too much from the starting vehicle, except for the trail that is initially longer. However, the suspension of this design is too soft and too low which causes undesired effects, such as front diving, wheelbase shortening, and lasting oscillations. Design 792, however, is quite different from the baseline motorcycle, e.g. the initial wheelbase is about 15 mm shorter and the chassis is inclined 4.7 deg forward. Suspension characteristics now appear adequate to prevent oscillations and excessive diving.

Finally and according to the optimization criteria, design 792 is the best choice. Presumably, the reduction of the stopping distance is not linked to the suspension update, but to the shorter wheelbase. Indeed, assuming that the ABS fixes the longitudinal slip, the braking force becomes proportional to the vertical load on the front tire, which is inversely proportional to the motorcycle length. To complete the research, both overall stability and handling capabilities should be investigated using a more sophisticated 3D model.

The design 792 saves about 2.3 m in stopping distance, which might be crucial in emergency maneuvers. Other objectives are less important, although improvements have been obtained as well, confirming the efficiency of the Multi-Objective optimizer.

Apart from the suggested application, this paper presents an innovative methodology for the design approach. modeFRONTIER provides capabilities for automatic and fast investigation of the various alternatives and offers smart tools to extract key information from the generated data.

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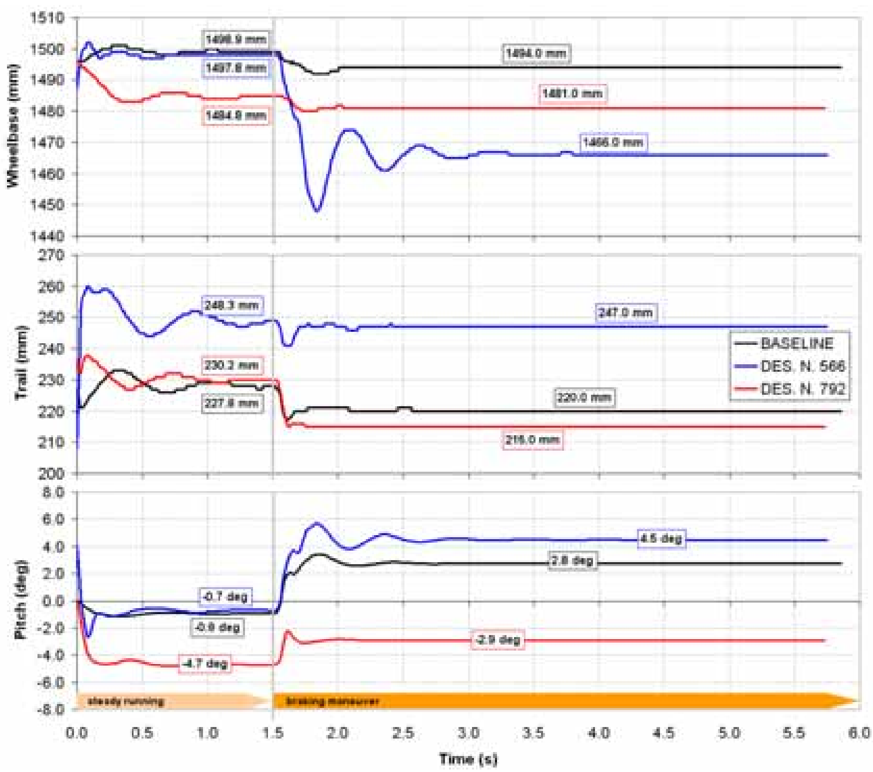

Figure 10 – Comparison between baseline and both optimized designs

The impact of multi-objective numerical optimization in Biomedical Engineering: a gallery of industrial cases

Nowadays, the demand for accurate and efficient design techniques is dramatically increasing in any engineering field. This motivates research institutions and universities to innovate and improve simulation methodologies and techniques faster than ever before. Numerical optimization, in combination with simulation, has a significant impact on this context: together, they allow, simultaneously, to improve the design, to shorten development times and to cut costs.

ES.TEC.O.'s modeFRONTIER optimization tool plays an important role in this technology: the software has the ability to couple and steer most of the commercial CAE tools and in-house codes, automating and allowing efficient optimization.
Here, in particular, some cases related to FEM and CFD in biomedical applications will be described. Emphasis will be put on the innovative approach and the application of optimization techniques. Hence, the aim of the work is to give an overview of the innovation chances that such procedures provide to researchers in this fast-developing engineering sector.

Introduction

The present work focuses mainly on the application of design of experiments, multi-objective optimization and robustness analysis technologies. Three examples are presented, the optimization of bone implants, blood pressure measurement devices and the design of an artificial lung.

Artificial lung design optimization

The first problem focuses on the application of multi-objective shape optimization techniques to improve the design of an artificial lung (Fig.1). The objectives here are the simultaneous reduction of the thrombogenicity and the increment of the gas-exchange performances of the device.

The volume of the domain with flow rate less than 0.5 mm/s could be considered as an index of thrombogenicity: this threshold value has been fixed with regard to the flow rate of aggregation of red blood cells in a thrombus formation process. Therefore, the first objective of the optimization will be the minimization of such volume ("Min LV").
The other objective is the minimization of the Standard Deviation of the flow rate in the fiber bundle ("Min SD"). This measure represents the gas exchange performances of the artificial lung, since blood should flow uniformly to the fiber bundle, avoiding stagnation and channeling.

Eight lengths were selected, to control the shape of the most important zones of the device geometry, accordingly to the freedom of the designer at the current stage of the product engineering phase (Fig.2).

The parametric CAD model of the lung was prepared, as well as automatic

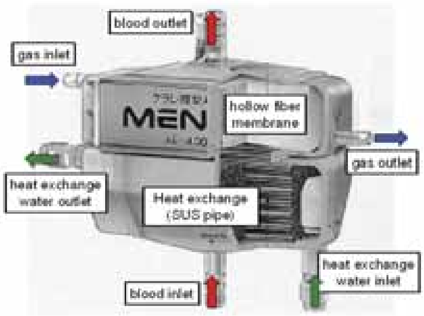

Figure 1. Artificial Lung design

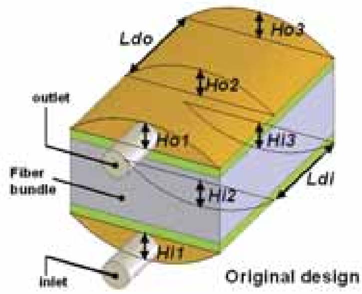

Figure 2. Parametric geometry definition on the CAD, ready for the design optimization

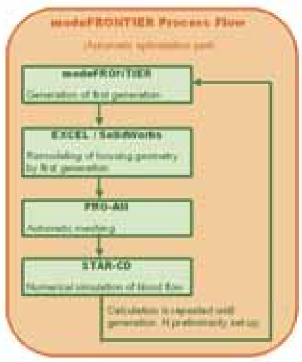

Figure 3. Scheme of the Process Integration realized by modeFRONTIER

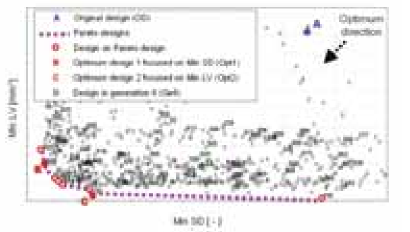

Figure 4. The set of optimal solutions in the space of the two objectives, as obtained by the MOGAII algorithm

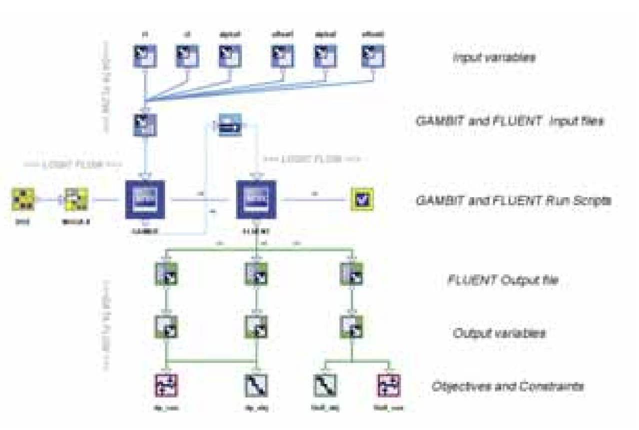

Figure 5. The schematic representation of the optimization loop within modeFRONTIER (workflow)

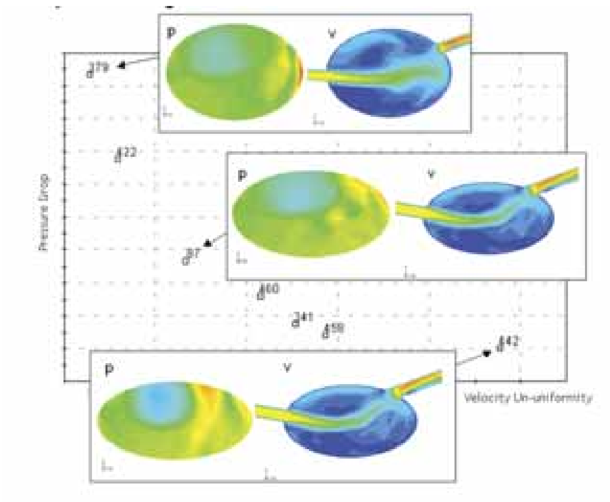

Figure 6. The Pareto Frontier with three different trade-off solutions.

meshing routines and the CFD model. The code integration and the optimization were carried out with modeFRONTIER (Fig.3).

Here, an improved Multi-Objective Genetic Algorithm (MOGAII) is used to solve the optimization problem, and promising results are obtained: simultaneous reduction of stagnation zones (anti-thrombogenicity) in the range of 70%, and flow rate standard deviation (gas exchange performance) reduced by 30% (Fig.4).

Medical blood pressure measurement device design optimization

The second case is based on the preliminary design of a medical blood pressure measurement device.

A probe is designed with the aim to minimize the pressure loss introduced into the blood flow, keeping the pressure uniformity at the outlet as high as possible. The computational chain, made up by the meshing and the CFD tools, was integrated and driven by the optimizer (Fig.5). The approach to this problem includes an exploration phase using Design of Experiments techniques, as well as a subsequent multi-objective optimization exploiting also response Surface Modeling techniques. This last feature has been used in order to accelerate the optimization process, replacing some CFD evaluations with such fast and accurate interpolations.

Once the set of optimal configurations (Pareto Frontier) was found, decision-making tools were used to find the best trade-off between the two different objectives (Fig.6).

Bone implant FEM model stochastic validation

The last section is dedicated to the stochastic validation of an implant.

The failure of cementless total hip replacements is mostly caused by aseptic loosening. Many authors consider the bone-implant relative micro-motion early after surgery (primary stability) as the main biomechanical cause of aseptic loosening in cementless implants. Animal and retrieval studies associate the failure of the osteo-integration process to primary micro-movements. The present study is based on the FEM of a human femur implanted with a cementless anatomical stem (Fig.7), modeling frictional contact at the bone/implant interface.

The aim is to evaluate the effect of some parameters on the predictions of the model (i.e. stress, strains). The model was fully validated in a previous work against primary stability experimental measurements. Cancellous and cortical bone were both considered homogeneous materials. The first was assumed isotropic, while the second was assumed transversally isotropic. The cementless stem was modeled as made of titanium alloy, with a modulus of 105000 MPa.

Stochastic input variables

Bone mechanical proprieties are derived by cortical and cancellous tissue apparent density analyses. Ranges of 1.5

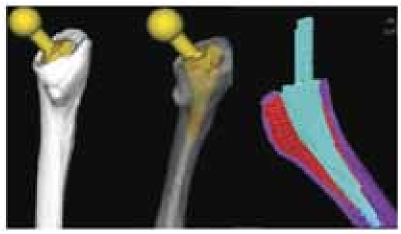

Figure 7. The FEM model, with its three material parts: cortical bone, spongy bone, stem.

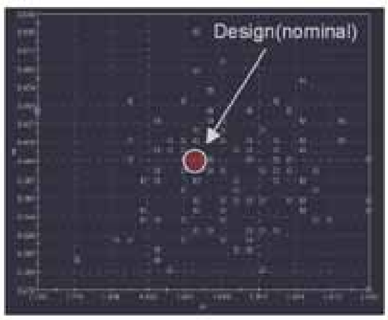

Figure 8. Multi-variate distribution on two of the stochastic input variables: the friction coefficient for the stem/spongy bone interfaces, and the one for the spongy bone/cortical bone.

– 2.0 gr/cm3 for the cortical bone and of 0.1 – 0.7 gr/cm3 for the cancellous bone are investigated: Gaussian function has been set for both parameters.

In total hip arthroplasty, different stem sizes are required because of the anatomical difference of patients' femurs. A scaling factor has been introduced to take into account nine different stem sizes (from 9 to 17), commonly used in surgery.

The sizes were assigned with the same probability: this parameter allows to investigate whether the most critical condition shows up with small or large anatomic dimensions. However, the most important aspect of the model is the bone/implant interface. Different interface conditions are taken into account, from the fully osseous-integrated condition to the presence of fibrous tissue at the bone implant interface.

The contact condition was therefore assigned to the seventeen zones defined as contact surfaces, accordingly to a uniform probability distribution. The magnitude on the loading force is described applying an hip contact force in the range of 1200-2580 N with a Gaussian distribution.

Output variables

Von Mises strain and stress are analyzed for the stem, cortical and cancellous bone (Fig.9). In addition, relative peak micro-motion and peak detachment were investigated at the bone implant interface, such as the "viable area" (defined as the fraction of the contact surface where micro-motions are under 40 microns). According to literature, this value can be considered as a threshold above which the osteo-integration process is strongly prevented. Peak contact pressures and peak frictional stresses are analyzed at the interface between the bone and the prosthesis.

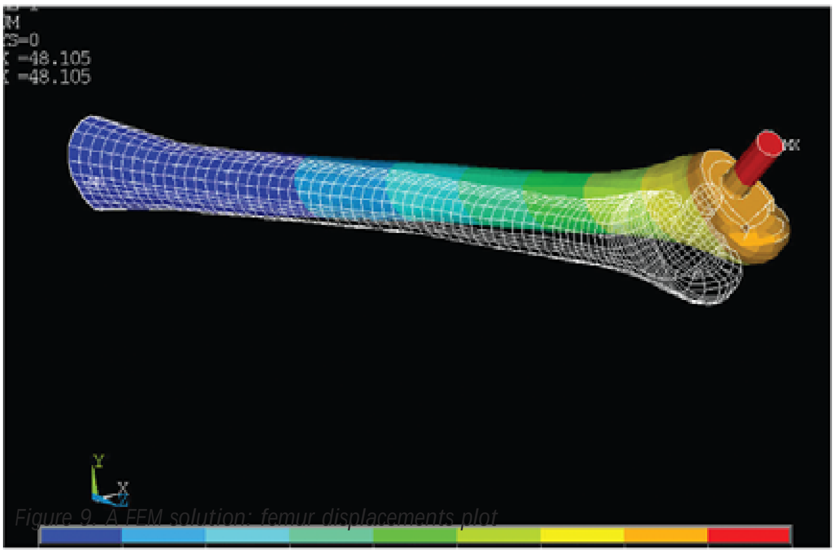

Figure 9. A FEM solution: femur displacements plot

Results

Stress and strain are strongly influenced by the femur-stem size, with an inverse relationship, as expected. Less effect is shown for the force magnitude, positively related. Spongy stresses are associated to the spongy apparent density with a positive relationship, while cortical strain and apparent density show an inverse relationship. Interface conditions seem not to have a strong global effect on the stresses and strains. However, high relationship is detected between the stress and the contact status of some selected zones: the reason should be probably found in the way the stem geometry transfers the loads to the bone.

Micro-motion parameters are influenced by the interface conditions, as expected. The contact viable area is correlated to the overall contact condition with an inverse relationship, while little effect is associated to the loading force and to the apparent density of both bone tissues.

At constant loading condition, the model predicts widely higher micro-motions for larger anatomies respect to smaller ones. As far as greater patients have usually also higher body weights, it is reasonable to state that the probability of stem aseptic loosening is higher for them.

Conclusions

The DOE, optimization and robust design technologies proved to be effective in several biomedical applications.
Their implementation, based on the modeFRONTIER environment, is straightforward, and can guarantee great improvements in design efficiency, time and cost savings, and productivity.

ACKNOWLEDGMENTS

Thanks to Mr. Ichiro Taga (Kawasumi Lab.s, Japan) who presented his work at the modeFRONTIER International Users' Meeting, 28th-29th September 2006 in Trieste, Italy.

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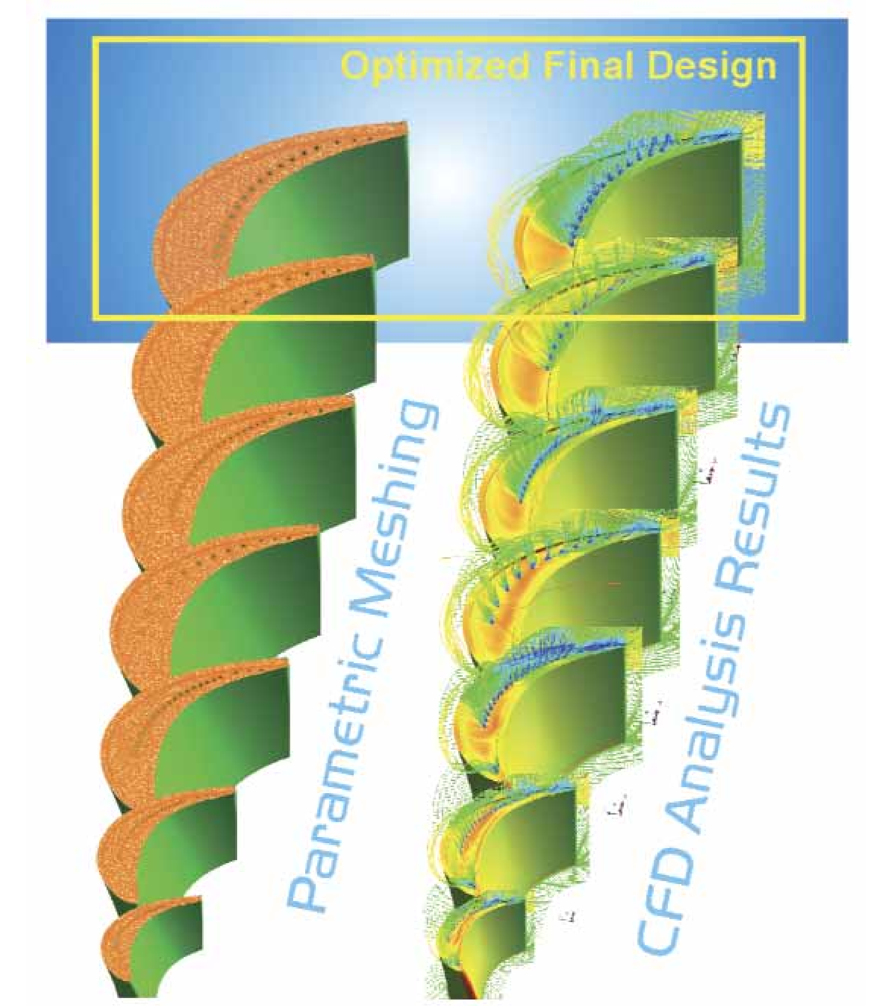
The present case study has been developed in cooperation with Laboratorio di Tecnologia Medica degli Istituti Ortopedici Rizzoli

Optimization of Gas Turbine Blades

Courtesy of Avio SpA

A novel methodology has been used to design the layout of the tip cooling nozzles of a high pressure rotor blade turbine. The methodology used is through a complete CAE approach, by means of a parametric CFD model which is run many times for the exploration of several designs by an optimizer.
Hence the design is carried out automatically by parallel computations, with the optimization algorithms taking the decisions rather than the design engineer. The engineer instead takes decision regarding the physical settings of the CFD model to employ, the number and the extension of the geometrical parameters of the blade tip holes and the optimization algorithms to be employed.



The final design of the tip cooling geometry found by the optimizer proved to be better than the base design (which used mean values of all input parameters) and also better than the design proposed by an experienced heat transfer AVIO engineer, who used standard best practice methods.

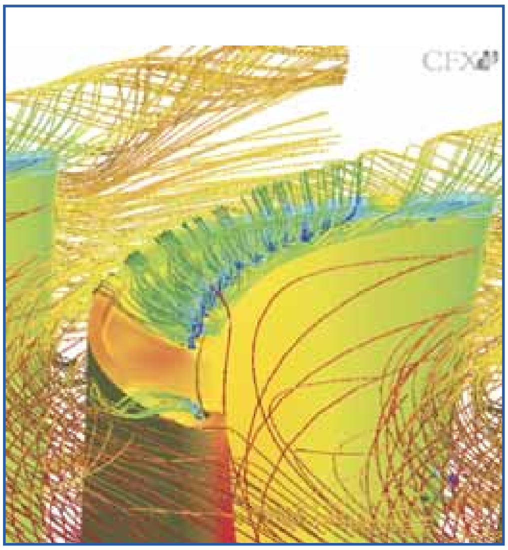
Tip Cooling Holes layout design via multi-objective genetic algoritms and artificial neural network expert system

Furthermore, through the large number of experiences gained the several simulations run by the optimizer generated a virtual database of tip cooling configurations, allowing the designer to find laws, functions and correlation between input parameters and performance output, with a further and deeper insight on this specific design blade cooling problem.

Methodology

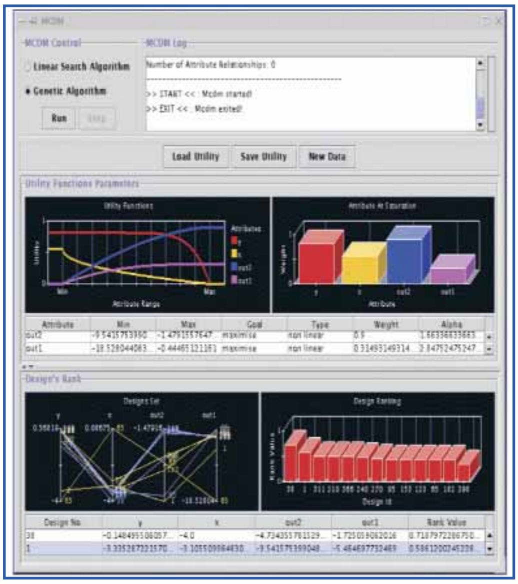
This study is part of an AVIO project concerning the development of High Pressure Turbine blades with advanced cooling systems. Due to the high gas temperatures entering the turbine of the most recent aero-engines, in general up to 2000 K at the turbine inlet at 40 bars, a very efficient cooling system is required in order to maintain the metal temperatures below the allowable limits. This means to use a certain amount of "cold" air directly extracted from the compressor, with a significant negative impact on the engine performance.

One of the most critical areas, from a thermal point of view, is the tip region of the unshrouded rotor blades. Tip regions are generally cooled using rotor internal air ejected in the flow path through a series of small holes located in the tip surfaces. The ejected air must cover all the surfaces in order to create a cold film between the hot gas and the metal. As the tip region is characterized by a very



complex 3D flow field, it is very difficult to optimize the cooling system using standard design methodologies, also considering the other blade tip requirements such as minimizing the hot leakage air from pressure to suction side, which has a negative impact on turbine aerodynamic efficiency.

For these reasons, the area of the tip is investigated with a parametric CFD approach: a parametric model is run several times guided by an optimization algorithm, such that an optimal solution in terms of performance can be found.
This kind of approach requires to link an optimization software (modeFRONTIER) to a 3-D CFD code (ICEM-CFX5) with the goal to find the optimal values of some geometrical parameters of the tip area of the high pressure rotor blade, such that certain performance objectives are reached. As a consequence of the geometrical complexity of the problem and of the high computational time, the use of the interpolators or expert system techniques becomes compulsory if a 3-D fluid-dynamic optimization has to be approached.
Several methods are generally available within optimization software: RSM, ANN, etc. In this case, a ANN method was chosen because of the nonlinearity of the system.

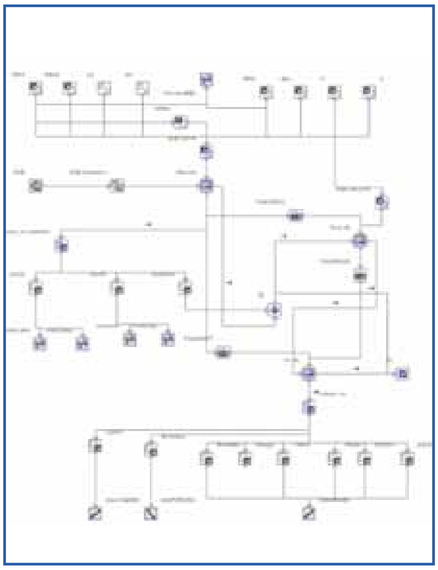


Blade cascade

This way, after a preliminary series of CFD analyses and after the estimation of ANN, the 3-D CFD model can be substituted by a series of mathematical functions and the computational time is considerably reduced. The expert system, represented by a ANN, must be introduced after a fair number of analyses are run, such that the expert system is reliable.

The error of the expert system is a known value and is the parameter which yields the accuracy of the interpolator relative to the database of real experiments so far acquired. It is up to the designer to chose the threshold error value of his expert system. Basically, the more CFD analysis we run, the more trained and the more accurate the expert system becomes, but with an increase of the CPU effort, and viceversa.
A parametric batch procedure allows the creation of different geometrical models, the mesh generation and the CFD analyses of the blades in an automatic way.
A series of preliminary CFD simulations is planned and a screening is performed in order to build an input-output database.
ANN coefficients for the two layers are calculated by the optimizer. A MOGA algorithm investigates runs with further CFD "Virtual" analysis, exploring the space of possible solutions on the ANN. Basically a virtual optimization of the cooling system is carried out without further CPU expensive CFD analysis.
The best virtual solutions are selected and the ANN virtual solutions are validated by a "real" CFD analysis.

More accurate Neural Nets can now be estimated with a larger database. The virtual optimization can be executed again and new and more performing designs can be found. This procedure is repeated till the desired convergence to the set of optimal solutions is achieved.
Finally, a layout of tip cooling nozzles is found by the optimizer and validated by a CFD analysis.



The final design chosen proved to yield the same heat transfer performance with a reduction of approximately 16% of the cooling air required. Hence we can conclude that a remarkable increase of performance of 16% is obtained thanks to an innovative complete CAE design process with CFD parametric models evolved by optimization algorithms.

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Gear Noise Reduction by numerical optimization of macro-geometrical and micro-geometrical design parameters

A numerical optimization process has been carried out in order to improve the performances of two helicoidal gears (here called pinion and gear) used to move the oil pump of a four cylinder diesel engine for a light commercial vehicle application. In particular the aim of this activity has been to reduce, the noise generated by the gears under the normal operating conditions without penalizing their strength and reliability. To do this modeFRONTIER has been used together with Helical3D which is a commercial software performing three-dimensional finite element analyses of gears taking into account the contact problem.

Among the several outputs deriving from a Helical3D analysis the most significant ones have been chosen as objectives of the optimization: the maximum bending stress at the tooth root of each gear, the maximum contact pressure and the peak to peak transmission error (PPTE). The first quantities are related to the gear reliability whereas the last one can be considered as a noise indicator.

At the end of the optimization activity, the predicted PPTE has been reduced by 70% without affecting the calculated gear reliability.

Input and output variables

The input variables for the optimization have been divided into two categories:

- the macro-geometrical variables are those which affect the gear size and the tooth shape;
- the micro-geometrical variables are used to modify the theoretical tooth profile in order to improve the gear functioning.

The quantities chosen as output variables are:

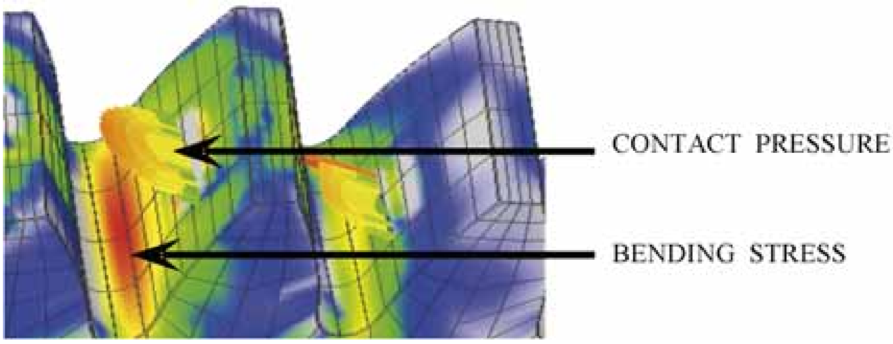
- the maximum pinion and gear bending stress at the tooth root (Pic. 1).
- the maximum contact pressure (Pic. 1).
- the peak to peak transmission error. It is computed as the amplitude of the gears angular tilting, that is the amplitude of the difference between the actual and the theoretical angular displacement 0 (Pic. 2). Generally speaking, the PPTE depends on the tooth stiffness: the more flexible the tooth is, the more it can bend and follow the gear movement. This kind of behavior smoothes the sharpness of the tilting reducing the PPTE.

Objectives and constraints:
The optimization process has been performed with the following objectives:

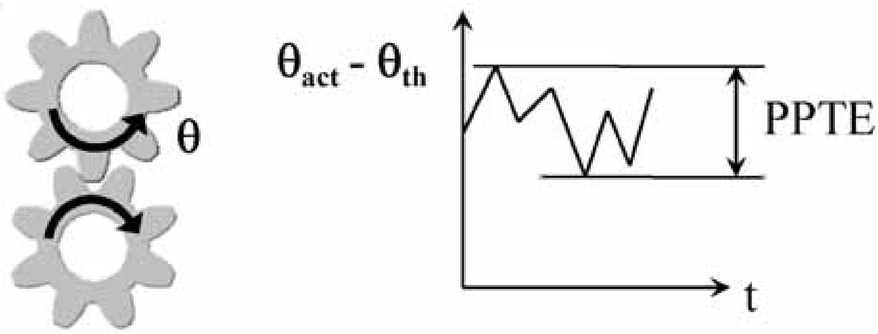
- to minimize the maximum bending stresses;
- to minimize the maximum contact pressure;
- to minimize the PPTE.

Moreover, some constraints have been set, in particular:

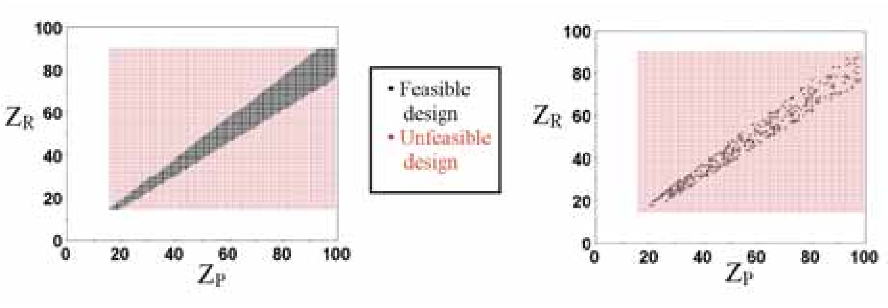
- the maximum bending stresses below, the material bending strength;
- the maximum contact pressure below, the material pressure limit.



Picture 1: Bending stress and contact pressure computed by Helical3D



Picture 2: Peak to peak transmission error definition



Picture 3: Feasible designs in comparison with the whole design space. On the left, the effect of the only transmission ratio constraint, on the right, the effect of both constraints

Optimization strategy

A first attempt to run an optimization process has been tried using the macro-geometrical variables. As the Pic. 3 shows, this definition of the input variables causes the feasible design space to be too small compared to the whole design space defined by the complete range of the input variables. This involves some problems for the DOE and optimization algorithms.

So the model has been modified changing some discrete type constrained variables into new ones characterized by continuous ranges. This kind of variable transformation stretches the original feasible space into a new one where no constraint is necessary.

The new model has been used to carry out an optimization in two steps: in the first step only the macro-geometrical parameters have been considered to be variable, whereas the micro-geometrical ones have been kept constant at the current value; the second optimization step has been done considering both the macro- and micro-geometrical parameters as variables.

Each optimization step was done following an iterative procedure, performed until the response surfaces accuracy reached a target value.

Results

The contact pressure response surface shows in the first step smaller errors than in the second step. This is due to the micro-geometrical variables which affect mostly the contact pressure.

The PPTE has shown itself to be a very difficult quantity to be interpolated as the high errors found for its response surface demonstrate. At the end of each step the Pareto frontier has been found (Fig. 4) and the decisional procedure applied. As a result, it is possible to compare the PPTE computed for the current design to the best designs after the first and the second step (Fig. 5). It can be noted that the optimization process has lead to a PPTE reduction of about 70%.

Conclusions

modeFRONTIER has been used for a gear optimization in order to reduce the predicted noise as much as possible, preserving the structural reliability of the current design. It has been easily interfaced with Helical3D which is a commercial software for three-dimensional analyses of gears.

The response surface tool has proved to be particularly useful with regard to the very long calculation time necessary to perform a great number of simulations.

In conclusion it can be stated that the use of a multi-disciplinary optimization software such as modeFRONTIER permitted the computed performances of the analysed gears to improve considerably.

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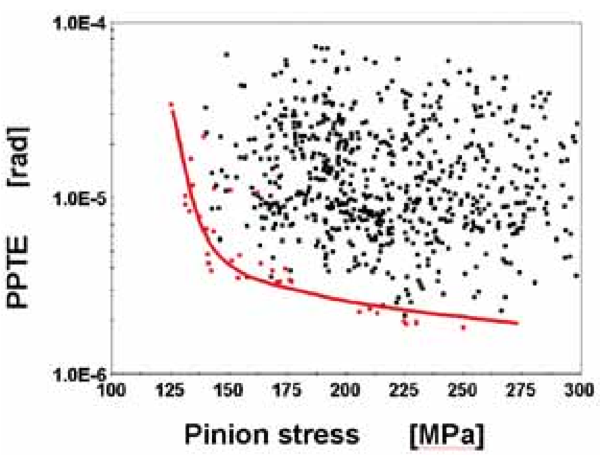
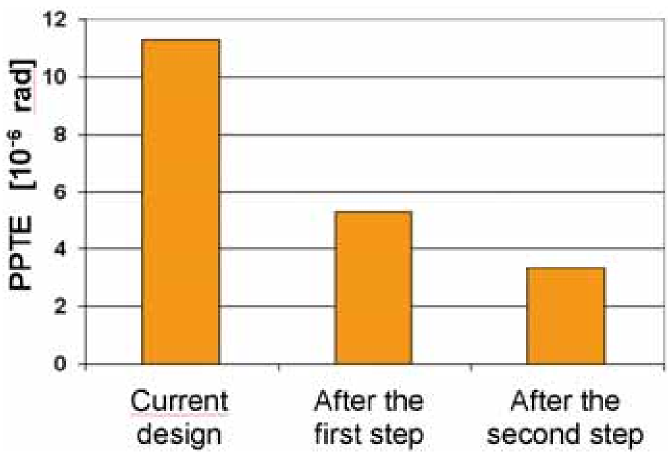


Picture 4: Section of the Pareto frontier in the plane PPTE-Pinion stress



Picture 5: PPTE comparison between the current design and the best designs after the first and the second step

Innovative PERM injection system design within the NEWAC EC Project

Abbreviations

ACARE: Advisory Council for Aeronautical Research in Europe
ANTLE: Affordable Near-Term Low Emissions
CAEP: Committee for Aviation Environment Protection
CAE: Computer-Aided Engineering
CFD: Computational Fluid-Dynamics
CLEAN: Component vaLidator for ENvironmentally-friendly Aero-Engine
EEFAE: Efficient, Environmentally Friendly Aero-Engine
ESTECO: EnginSoft TECnologie per l'Ottimizzazione
MOGA: Multi Objective Genetic Algorithm
NEWAC: NEW Aero Engine Core concept
OPR: Overall Pressure Ratio
PERM: Partially Evaporating Rapid Mixing
SRA: Strategic Research Agenda
VITAL: enVIronmenTALly Friendly Aero Engine)

Introduction

NEWAC is an initiative from the Engine Industry Management Group that integrates European aero engine manufacturers, the main European aircraft manufacturer (Airbus), small and medium enterprises and industries providing innovative technologies, as well as leading research institutions in the field of aeronautics to provide a step change for low emission engines by introducing new innovative core configurations to strongly reduce CO2 and NO_X emissions.

State of the art of Aero Engines

Global air traffic is estimate to grow at an average annual rate of about 5% in the next 20 years. This scenario urgently requires to address environmental penalties: the gases and particles emitted by engines contribute to local air quality degradation in airport vicinities and alter the concentration of greenhouse gases on a global level, leading to climate change. Thus, Europe's aviation industry faces a considerable challenge to satisfy the demand whilst ensuring economic, safe and environmentally friendly air travel.

Large investments have already been made in Europe and the US through R&D programmes and collaborations to reduce the negative environmental effects of aircraft use. In fact, research provides the technologies to improve the performance of existing engine components.

However, even if these technologies

CFD aerodynamic study and MOGA optimization of the air distribution layout for a medium pressure Combustor

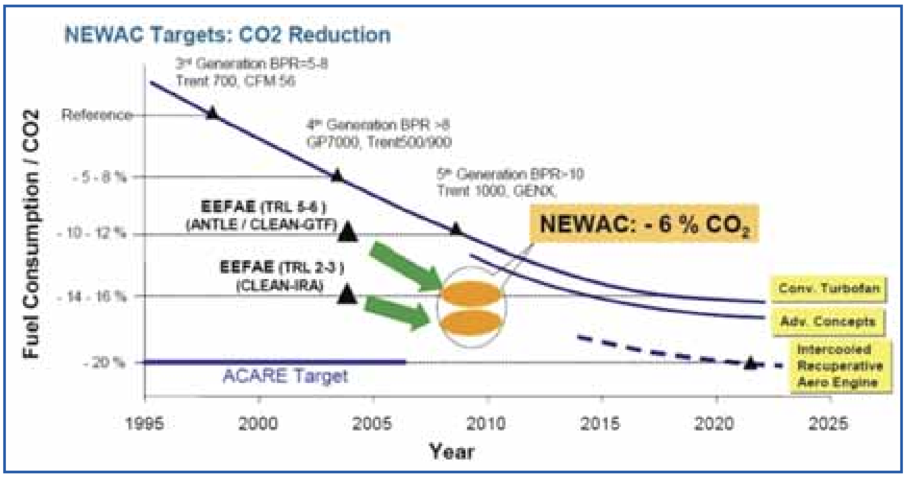


Figure 1: Fuel consumption / CO2 reduction for different core concepts: Newac vs. state of the art

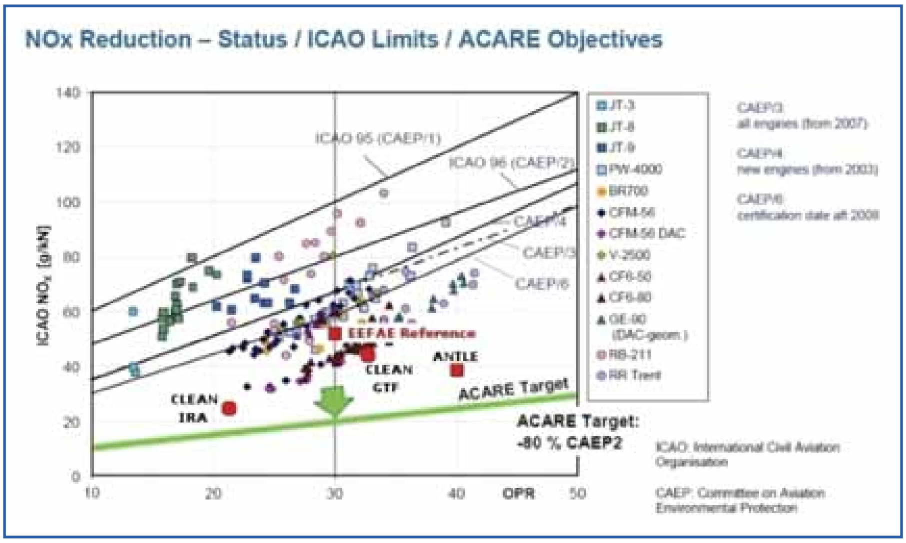


Figure 2: NO_X reduction for different core concepts: NEWAC vs. state of the art

permit improvements in emissions, their existing limitations will not allow the industry to reach the goals set in ACARE: to reduce NO_X and CO2 emissions and to achieve the ACARE objectives, it is now mandatory to develop new engine configurations and to perform complementary research and development of core engine technologies (high pressure system).

Objectives

ACARE identified the research needs for the aeronautics industry for 2020, as described in the ACARE SRA. Amongst others, the following targets regarding the engine are set, which will be looked for by NEWAC:

- 20% reduction in CO2 emissions per passenger-kilometre whilst keeping specific weight of the engine constant (see Figure 1);
- significant reduction of NO_X emissions during the landing and take-off cycle (-80%) and in cruise (-60%) respect to CAEP/2 limit (see Figure 2).

The main result of NEWAC will be fully validated, novel technologies enabling a 6% reduction in CO2 emission and a 16% reduction in NO_X according to landing and take-off cycle versus the CAEP/2 limit. These results will be integrated with past and existing EC Projects in the field, notably EEFAE (-11% CO2, -60% NOX), VITAL (-7% CO2) and national programmes, thus CO2 can be reduced up to 20% and NO_X close to 80%, hence enabling European manufacturers to attain the ACARE 2020 global targets.

The project will address the particular challenge in delivering these benefits simultaneously: many technological developments based on conventional thermodynamic cycles are driven to high temperature and pressure levels to reduce CO2 whilst compromising NO_X emissions.

To avoid this conflict a number of innovative core engine concepts will be investigated and key components will be tested and evaluated. All concepts will be based on single annular combustor architecture that offers the highest potential to keep penalties on weight and associated cost with the introduction of lean low emission combustion technology at acceptable levels. On the other hand, the different operating conditions of the various engine sizes will require the improvement of individual lean burn fuel injection concepts. Starting from these models, each partner works on the definition of a new operating configuration.

In addition to technical objectives, NEWAC will lead to the deployment of the technology by preparing the European engine supply chain, including internal production departments of the NEWAC contractors, through dissemination and training actions. NEWAC will also provide a basis for information to be used for the establishment of future legislation aiming at increasing stringency in NO_X and CO2 regulations in the aerospace sector.

Added value of an integrated project

NEWAC conforms to the priorities defined for an integrated project framework by conducting multi-disciplinary research on compressors, combustors, core engines, intercoolers, recuperators, ducting, materials and more generally engine design.

The key benefit of integrating these technologies into one project is that, were these technologies to be developed individually or in separate smaller projects, they would have a very limited benefit at engine level; however, when focused and combined as in the NEWAC integrated project, together they enable new designs of core engines that will provide significant benefits.

EnginSoft's first year task within NEWAC

For a decade and through its CFD team, EnginSoft is strongly involved in combustion activities. The team is particularly active in research projects funded by the EC which have a focus on low emissions, and thus address the environmental impact due to air traffic, which accounts for 2% of the total global emissions.

In the past, EnginSoft has been involved in activities within the ANTLE, TATEF and CLEAN programme for heat transfer and combustion optimization applications. Such activities were also among the first to employ the novel developed optimization platform modeFRONTIER for industrial applications.

Thanks to its broad expertise in CAE (process simulation, CFD, optimization of design), EnginSoft is one of the 40 partners of NEWAC. The main role of EnginSoft in NEWAC, as a subtask of the Project, is to bring a contribution to the design of the Ultra Low NOx AVIO Single Annular Combustor, by means of:

- the optimization of an innovative injection system technology called PERM (Partially Evaporating Rapid Mixing), applied to medium overall pressure ratios (20 < OPR < 35): the concept is based on swirler technology development and is addressed to achieve partial evaporation and rapid mixing within the combustor, optimizing the location of the flame and the stability of the lean system;
- the design of a Ultra Low NOX combustor chamber, focusing on the optimization of the architecture;
- the improvement of other critical

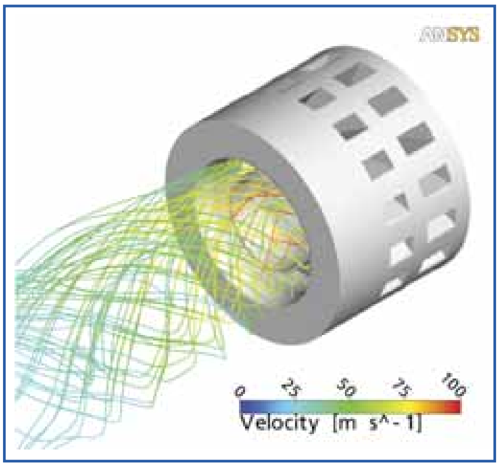


Figure 3: Injection system

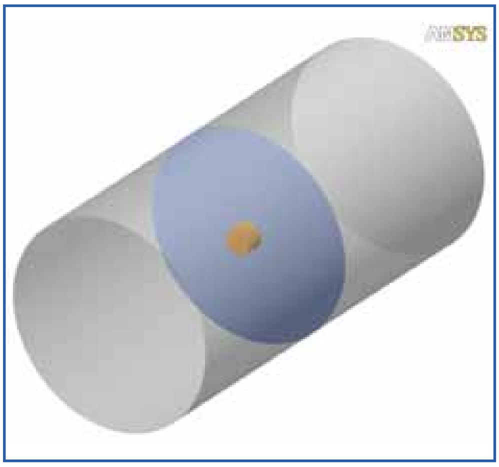


Figure 4: Avio test rig

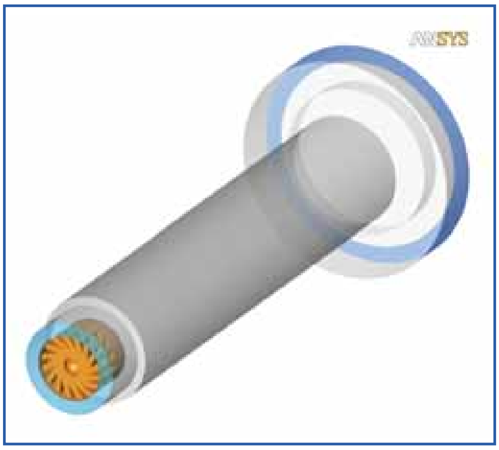


Figure 5: University of Karlsruhe test rig

lean combustion technologies, such as advanced cooling systems, fuel control systems and fuel staging concepts.

Innovative Combustor

The combustion system is the only contributor to NO_X emissions. Lean combustion technology operates with an excess of air to significantly lower flame temperatures and consequently significantly reduce NO_X formation. Up to 70% of the total combustor air flow has to be premixed with the fuel before entering the reaction zone within the combustor module. Therefore, cooling flow has to be reduced accordingly to provide sufficient air for mixing. Lean combustion comprises the lean direct injection of fuel, premixing with air and at least a partial pre-vaporisation of the fuel before initiating the combustion process.

The optimization of homogeneous fuel-air mixtures is the key to achieve lower flame temperatures and hence lower thermal NO_X formation.

However, this homogenization has a strongly adverse effect on combustion lean stability, drastically narrowing the operating and stability range. To overcome these stability drawbacks while maintaining good NO_X performance, fuel staging is required: this can be performed by internally staged injectors in a single annular combustor architecture creating a pilot and a main combustion zone downstream of a common fuel injector.

Injection system

The first NEWAC activity carried out by EnginSoft is the investigation of the aerodynamic behavior of the PERM injection system developed by AVIO and tested by University of Karlsruhe.

The device consists of a co-rotating double swirler centripetal injector. The injection system is illustrated in Figure 3. The mixer is composed by 2 swirlers (primary and secondary) with 16 radial channels each.

The purpose of the CFD analysis and experimental tests on injection system is to individuate the swirler working flow function, hence the mass flow required in order to reduce emissions under the available pressurization (depending on engine layout). Moreover, the numerical analysis verifies that the injection system provides good mixing and recirculation for future flame stability.

In particular, the aim of this activity is to point out any meaningful difference on the injection system performance, depending on:

- Plenums sensitivity: injection system performance has been compared between a large plenum simulating experimental test rig proposed by AVIO (Figure 4) and a small plenum with annular blockage on the outlet simulating engine rig condition proposed by University of Karlsruhe (Figure 5).
- Transient vs. steady state flow field: velocity and pressure fields generated from an aeronautical engine swirled injection system have a typical non stationary behavior, as many articles and publications demonstrate; hence transient studies on these models are useful to evaluate the approximation when the adopted simulation type is steady-state only.

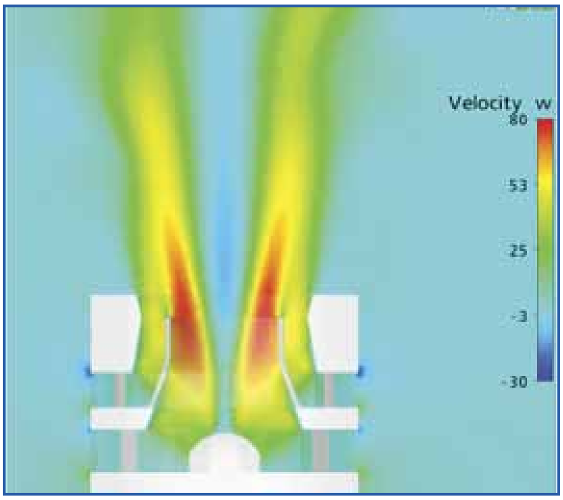


Figure 6: Axial velocity – Avio test rig

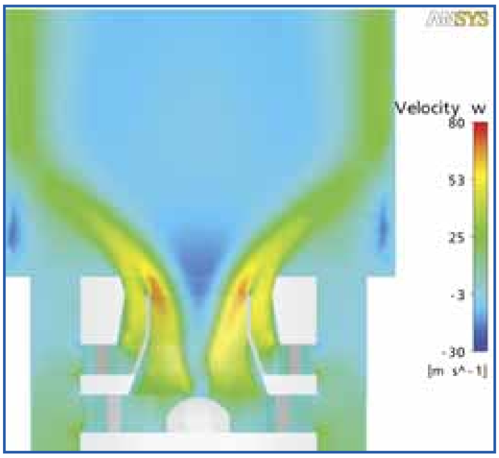
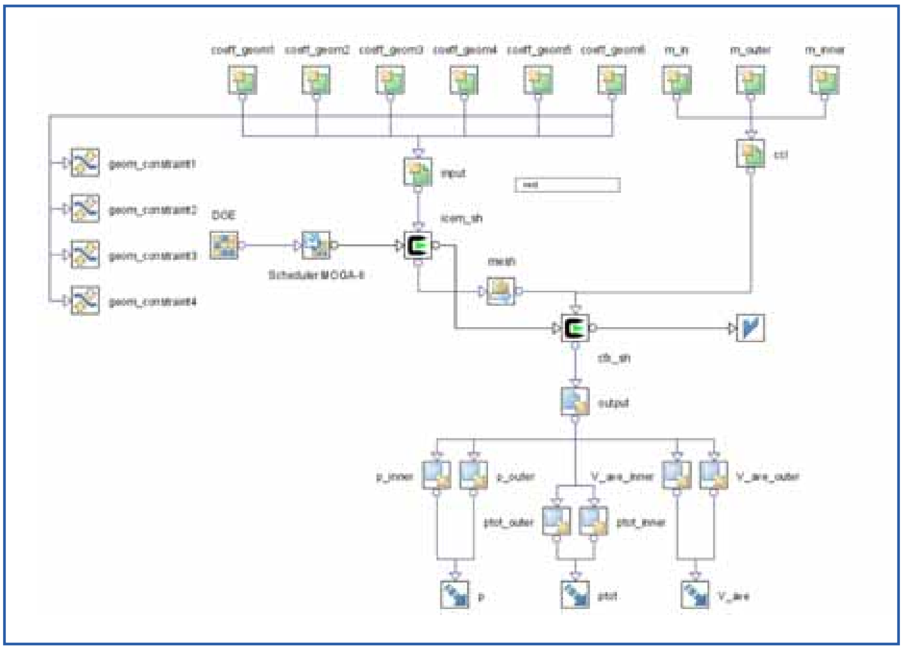


Figure 7: Axial velocity – University of Karlsruhe test rig

Furthermore, turbulence model sensitivity was addressed comparing standard K-espilon with Prandtl Number modifications with SST formulations in both RANS and URANS mode.

The sensitivity analyses on the pressure plenums showed that geometrical downstream chamber shape strongly affect air distribution (see Figures 6-7): the flow field in the University of Karlsruhe model is strongly canalised (downstream chamber diameter is only two times larger than the injection system diameter), while in the Avio test rig model, the flow develops freely in a constant pressure much wider plenum. The recirculation areas/volumes for flame stabilization are completely different, being more open in the Karlsruhe test rig and much narrower, with a stronger axial flow, in the Avio test rig. Moreover, the large plenum (Avio) yields a mass flow ratio between the primary and secondary swirler channels of 1.12, whereas the small one (Karlsruhe) with identical boundary conditions yields nearly an inverted ratio of 0.82. Hence the mixing performance is very sensitive to the pressure plenum geometry and BCS.

Results of steady state analyses are close to time averaged results of unsteady state ones. Although a steady state simulation does not give any frequency information, it can be adopted as good approximation as it allows significant CPU time savings and supplies useful data to evaluate the performance of the injection system.



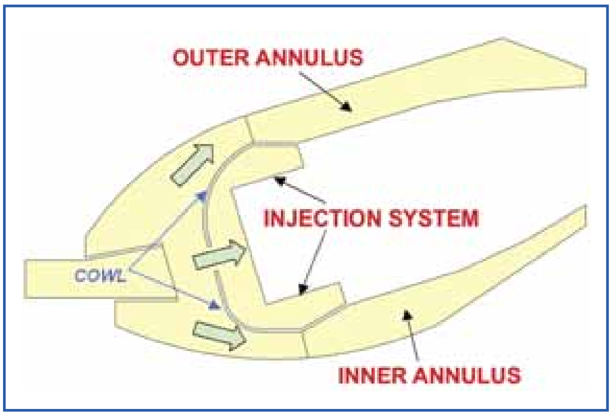


Figure 8: Combustor chamber sketch

Cowl

In a typical aeronautical engine, the air coming from the compressor is discharged into a pre-diffuser that converts a portion of dynamic pressure to static pressure. Then a diffuser receives the air at the pre-diffuser exit and supplies it to and around an aerodynamically shaped cowl, placed ahead of the injection system.

This cowl usually splits the air into three parts: one is the cowl passage to supply air to the injection system and for dome cooling; the others are feeding the outer and inner annulus passages, where air is introduced in the combustor chamber to cool the walls through liners, break the swirl and constrain the combustion area through the dilution holes while the rest exits through the bleed holes.

Different cowl geometry configurations have been evaluated to find the best shape in terms of obtaining good pressurization levels for the injection system and along inner and outer annulus. The velocity field is also of interest as a bad profile can raise separation and recirculation, resulting in a counterproductive pressure drop.

To simplify this work phase, a preliminary 2D study has been performed to provide a general suggestion of the behavior of the fluid upstream the combustor chamber.

For this purpose, it is useful to apply the multi-objective optimization technology modeFRONTIER by ESTECO.

This tool allows to automatically manage a series of processes acting on input parameters in order to achieve the

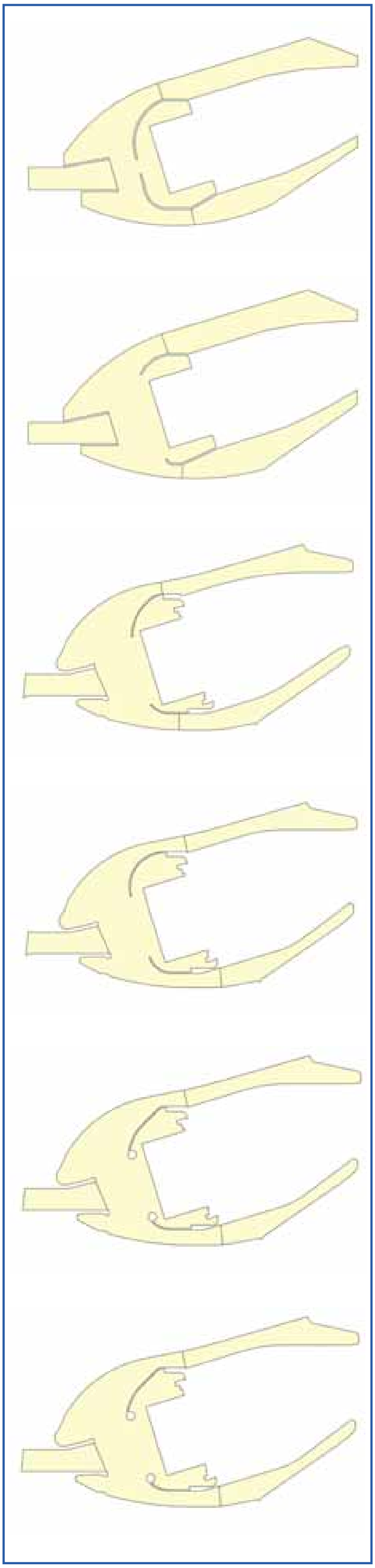


Figure 10: Cowl 2D study – Model evolution supplied by modeFRONTIER

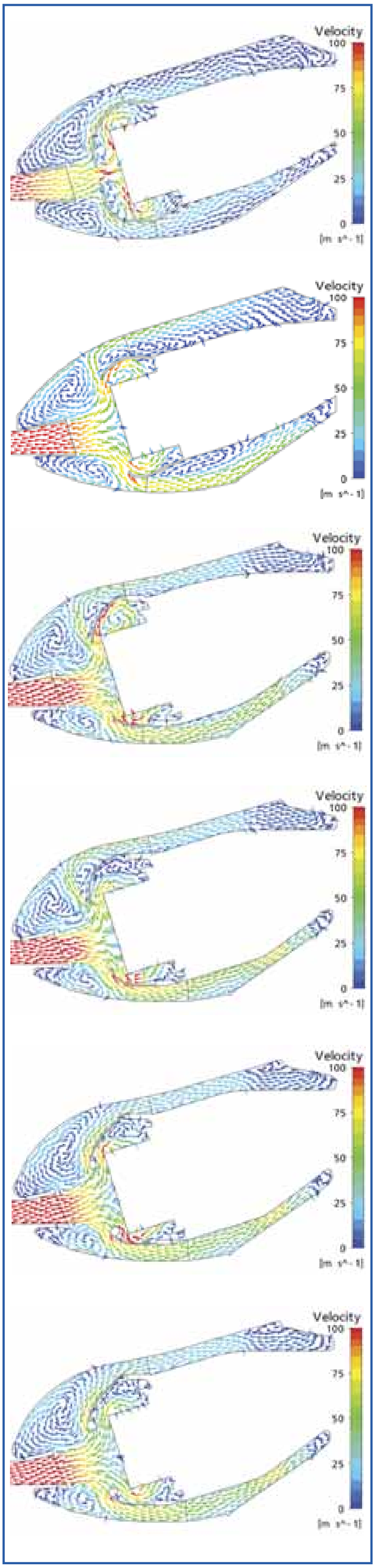


Figure 11: Cowl 2D study – Velocity field

optimal solution according to imposed constraints and objectives. In this case:

- input geometric parameters (curvature, length, position) define the cowl model to be evaluated;
- parametric meshing, CFD simulations and an automatic post-processing procedure are the processes involved;
- the target pressurization level and air splits on the annulus are the system's constraints and objectives.

The optimization algorithm is MOGA-II. It is an efficient multi-objective genetic algorithm (MOGA) that uses a smart multi-search elitism. This elitism operator is able to preserve some excellent solutions without bringing premature convergence to local optimal fronts. MOGA-II requires only very few user-provided parameters (such as a number of generations, probability of cross-over, selection and mutation), while several other parameters are internally settled in order to provide robustness and efficiency to the optimizer.

In Figure 9 the PIDO (Process Integration Design Optimization) Logic flow which integrates the parametric ICEM scripting and CFX analysis into a modeFRONTIER workflow, is shown.

modeFRONTIER supplies several good candidates, such as those in Figure 10. The last configuration represents the best candidate, since there are no evident separation problems relevant to the cowl edges or injection system (Figure 11).

The results derived from the 2D study have been applied in a 3D investigation on a simplified periodic sector of the actual annular combustor (the simplification consists of considering no flame tube, no liners and simplified bleed holes at the annulus end).

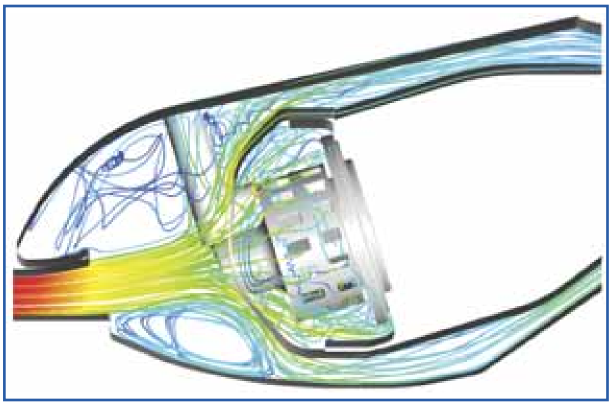


Figure 12: Cowl 3D study

Several configurations have been taken into account in order to find the best pressurization level feeding the injection system and the air split through inner/outer annulus.

Since 3D effects become fundamental, the attention has been focused on cowl shape refinement. Moreover, a preliminary fuel tube has been introduced into the model. This obstruction deeply affects the velocity field generating a wake in the outer annulus.

From all the analysed configurations, only the best one in terms of optimal pressure and velocity fields has been applied to complete combustor analyses (Figure 12).

Complete combustor

The final stage of the aerodynamic study deals with a periodic sector of the complete combustor: flame tube, liners and bleed holes (with downstream plenums) are now considered (Figure 13).
Compared to conventional combustors, with chambers now in production the main difference is that up to 70% of the total air flow passes through the injection system, leaving only 30% for the inner/outer annuls and successively the liners, dilution and bleed holes. Hence as the cooling and dilution air strongly diminished, the dilution rows are reduced to just one with no differentiation between primary and secondary dilution holes.

The objective in this stage is to reach the best layout for dilution holes in order to optimize the combustion process. Acting on holes' diameters and positions, it is possible to change air distribution and dilution flow diffusion: these aspects contribute to create a recirculating region that guarantees flame stability for cooling. modeFRONTIER will be useful in future activities within this task to evaluate several diffusion holes' arrangements to optimize the air flow split and, consequently, the combustion process.
Hence this future activity will have to consider reacting flows thus increasing the complexity of the model, and introducing performance targets, such as Nox, OTDF and RTDF profile constraints.

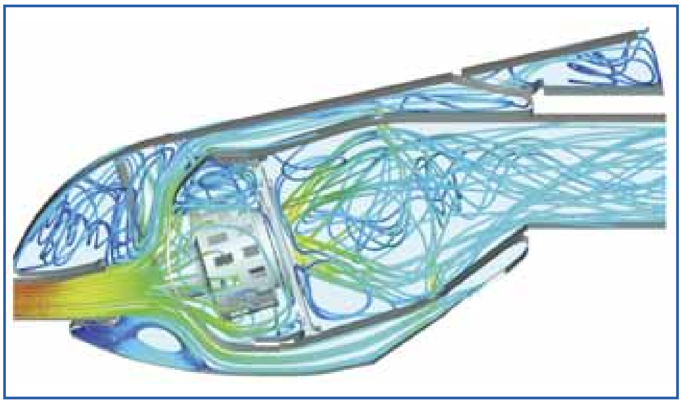


Figure 13: Complete combustor study

Conclusions

The NEWAC program has been an important opportunity to develop an innovative methodology based on modeFRONTIER for application in the aerospace field. With this technique, a large number of virtual prototypes might be evaluated and a selection of the best designs may be made directly within the modeFRONTIER environment, avoiding a large number of prototype constructions and thus allowing a significant reduction of costs and time.
Future activities to be addressed for the continuation of the project are: injection system evaluation procedure, air flow split balancing optimization, reacting flow combustion performance for some points of the flight envelope.

All the aerodynamic and reacting flow results derived from this work will be useful for future NEWAC activities concerning the development of the innovative Injection System based on the PERM concept and the final optimization of the AVIO Combustor configuration in order to meet the performance targets for pollutant emissions.
For further information about the NEWAC Project, please visit:
www.newac.eu

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The Theory of Critical Distances: a Useful Tool for Failure Prediction

The prediction of fatigue, brittle fracture and other failure mechanisms that cause cracking is a continual problem for designers of engineering components and structures. But help is at hand. The Theory of Critical Distances is a method which can be easily interfaced to FEA and other types of stress analysis software. It is a simple and accurate method for estimating the effect of stress concentration features.

This is the first book ever to be written on this subject and will be of interest to industrial design engineers as well as researchers.

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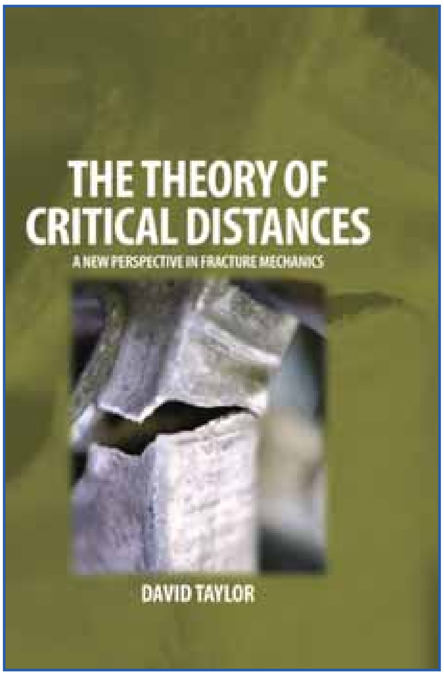
This article is a summary of the authors' experiences in using and developing the method over the last ten years.

Modern computational methods such as finite element analysis allow us to conduct accurate stress analysis, even for large, complex structures and components.

But how can we use this wealth of information to predict, and hopefully avoid, mechanical failure? There are many approaches to this problem but, as yet, no complete solution. Failure, by processes such as fatigue and brittle fracture, invariably starts from stress concentration features on components, features such as corners, holes, notches and defects.

The Theory of Critical Distances (TCD) offers a simple, practical option for the analysis of stress concentration features. It can be easily interfaced to FEA and is capable of the necessary level of accuracy when dealing with practical problems in design and failure analysis.

The TCD is not a new approach; it was suggested over fifty years ago, but



interest in the method has grown recently now that computing power allows us to describe stress fields in the vicinity of stress concentration features with the necessary resolution. The current state-of-the-art has been described in a recent book, the first ever to be written on this subject, which summarises the research conducted to date worldwide and contains many case studies and examples taken from the author's own consultancy work.

Fig.1 illustrates a typical industrial problem: the prediction of fatigue failure in a suspension component, a project which was carried out in collaboration with the Fiat Research Centre. Given its complex shape and load history, such a component contains many stress concentration features. The maximum stress was found to occur at Feature 1, a fillet with a very sharp corner radius. Conventional fatigue analysis packages in commercial FE software predicted failure at this location.
However, the TCD correctly predicted that failure would occur at Feature 2. Why did

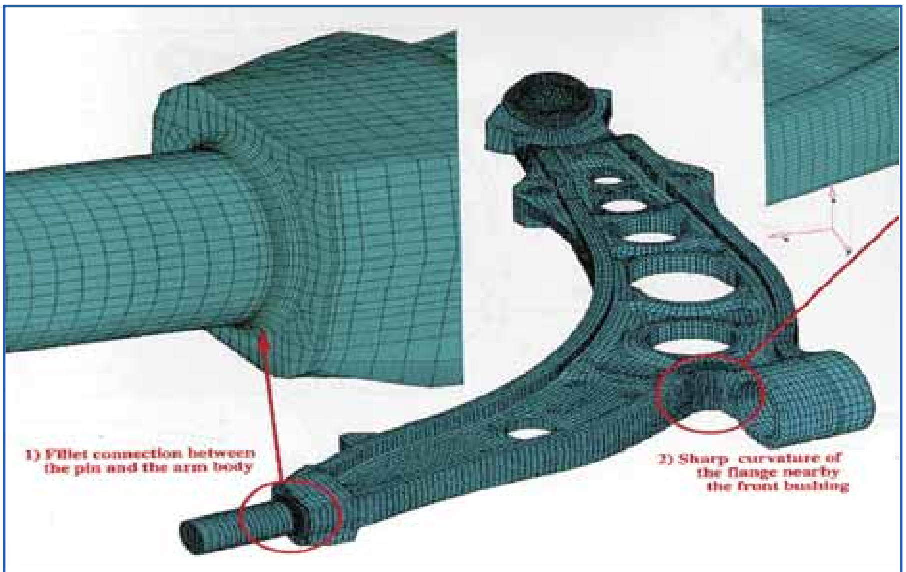


Figure 1: This Fiat suspension component contains many stress concentration features. The maximum stress occurs at the sharp corner of the fillet in Feature 1, but fatigue failures actually occurred from Feature 2. This unexpected outcome arises due to the differing stress gradients at the features. The TCD was able to correctly predict the outcome, and to estimate the number of cycles to failure.

this happen? The trick is to realise that the maximum stress is not the only important parameter; one also needs to know the stress gradient. In features such as the Feature 1, the stress decreases rapidly as one moves away from the feature, so the stressed volume is small. Fatigue cracks form easily at such features, but find it difficult to keep growing as they propagate into the lower-stress regions around them.

The TCD is a method which takes account of both maximum stress and stress gradient. In practice there are various ways of doing this which we do not have time to discuss in detail in this short article. The first step is to determine a parameter known as the critical distance, L. This parameter is assumed to be constant for the material, though in the case of fatigue it would be expected to vary with mean stress and the number of cycles to failure just as other material constants such as the fatigue limit will vary. The value of L can be determined either by conducting experiments on notched specimens or by using known relationships with other material properties. For example in the case of fatigue limit prediction one can use the following equation:

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta \sigma_o}\right)^2$$

Here ΔK_{th} is the material's crack propagation threshold stress intensity range and $\Delta \sigma_o$ is its fatigue limit.

The simplest methods in the TCD, which are also the ones most suited to post-processing FE results, are methods which examine the elastic stress field near the feature and use this to calculate a characteristic stress. For example, in the method which we call the Line Method (LM), the characteristic stress is the average stress calculated on a line of length 2L drawn from the maximum stress location (the 'hot spot'). Even simpler is the Point Method (PM), for which the characteristic stress is the stress at a single point, located a distance L/2 from the hot spot. Other methods are also available within the TCD, some of which use averaging over areas or volumes of material, whilst others involve the consideration of cracks whose lengths, or growth increments, are also a function of L. However, we have found that the PM and LM give very good accuracy, as will now be illustrated for two classic problems:

1) The effect of notch root radius. Fig.2 shows experimental data and predictions for the fatigue strength of notches with constant length and varying root radius. This is typical of a lot of data of this kind which we have analysed: the PM tends to be slightly more accurate than the LM, but typically both methods give errors of less than 20%.

2) Feature size. The effect of a feature such as a hole depends on its size because, whilst size may not alter the maximum stress, it will change the stress gradient. Smaller holes are less dangerous; this may be crucial when considering the effect of defects such as casting porosity or inclusions. The TCD can predict size effects very accurately: fig.3 shows an example: ceramic materials containing small defects.

This last example also illustrates the fact that the TCD can be applied not only to problems in fatigue but also to brittle fracture under monotonic loads. In principle it can be used for any situation where failure occurs by cracking: we have already applied it to problems in fretting fatigue and crack propagation through both brittle and ductile materials.

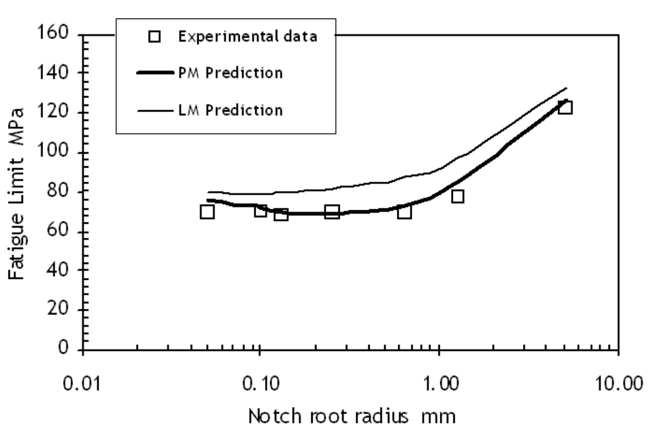


Figure 2: A classic problem in metal fatigue: the effect of notch root radius on the high-cycle fatigue limit. Experimental data on steel can be accurately predicted using the Point Method (PM), or the Line Method (LM), though the latter gives a small non-conservative error.

It is applicable to all kinds of materials: for example it is being extensively used to assess structures made from fibre composite laminates such as aircraft wings and bridges.
Multiaxial loading is a subject of great importance for industrial components, especially as regards their fatigue behaviour. Stress concentration features often experience combinations of tension, shear and torsion, both in-phase and out-of-phase with each other. In some recent work we showed that the TCD could be successfully applied to predict the high-cycle fatigue behaviour of specimens containing notches, subjected to various types of multiaxial loading.

Extra complexity arises here because of the three-dimensional nature of the problem. To solve this, we developed a strategy for selecting the appropriate point or line for use with the PM and LM respectively, allowing us to use the TCD in conjunction with existing theories of the critical-plane type. Further work is needed to consider the effect of variable amplitude loading, but in principle there is no reason why existing methods such as rainflow counting cannot be used in

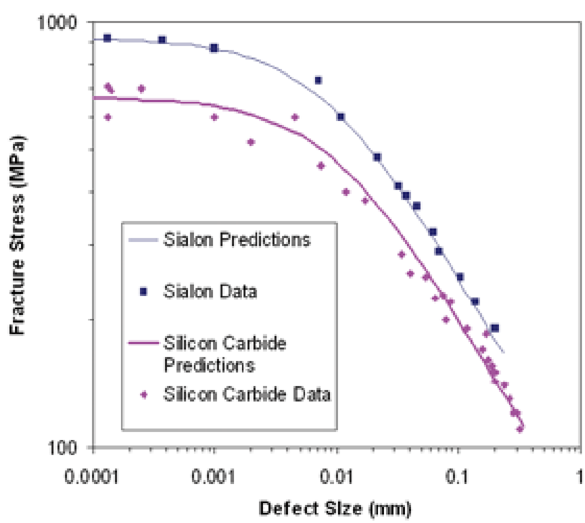


Figure 3: The effect of small defects on the stress to cause brittle fracture under monotonic loading of two ceramic materials: silicon carbide and sialon. These materials are highly sensitive to defects: the TCD gives very accurate predictions.

conjunction with the TCD.

Further information can be obtained from the listed references or by contacting the authors. We are very interested in hearing about the experiences of others in using the TCD and in working together with industrial designers to improve the method and extend its range of applicability.

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Luca Susmel, University of Ferrara - Italy

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Computer Aided Engineering in the TechNet Alliance

TechNetAlliance

From its commercial introduction in the early 1970s, CAE has been used to validate the designs of automobiles, machinery, nuclear power plants, electronics, and consumer products.

More recently, some of the world's best CAE talent has turned its attention toward the „greener" side of design.

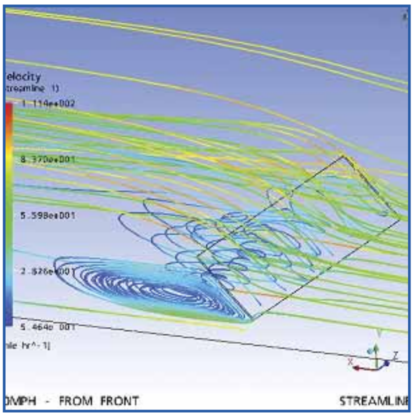
As the world seeks alternative energy sources, and strives to find lest costly and more environmentally friendly solutions, the value of CAE has once again, found a welcome home.

The TechNet Alliance is a global network of CAE experts, whose members have already demonstrated the potential for CAE simulation in this emerging field.

The following part of this article provides a sampling of some of the work underway by members of TechNet Alliance, and will provide a glimpse into the future potential of CAE simulation.

Solar Panels

Ozen Engineering, Inc. performed simulations on the support structures for a solar panel „farm" to determine



CFD Simulation of a solar panel

the forces acting on large solar panels under high wind conditions.

The results from these simulations were used to determine the design of the support structure for these solar panels.

Wind Turbines

Simulation Research investigated the energy produced by wind power. Within their analysis they took care of all components in the system, the wind turbine, the pitch control and the electrical machine.

Hybrid Electrical Vehicles (HEV)

- **Electronics.** By using products such as ANSYS and CASPOC, Simulation Research was able to investigate the influence of both mechanical and electrical components of a vehicle. The net effect of all simulations was the development of a balance vehicle with proper controls, and balance between the combustion engine and the electric motor.

- **Electrical Drives and Actuators** are the fields of interest of Prof. Dr.-Ing. Dieter Gerling, who is currently holding a chair at the University of the Federal Armed Forces Munich and has special expertise in hybrid electric machines, permanent magnet machines, electric drives and wheel-hub drives. Together with the Institute EAA of our Honorary Member, Professor Gerling, CADFEM is involved in a research project „Computer Aided Macromodelling of Electromecha-nical Systems".

- **Power Pack Systems Mindware Engineering, Inc.** has extensive experience in utilizing simulation technology to optimize the thermal management behaviour of various power pack systems to extend the life of the battery cells.

- **Fuel Cells. Sherpa Engineering** focuses on the system efficiency, dynamic design, control and diagnosis of automotive fuel cell propulsion systems. The main topic of Sherpa Engineering currently is the development of a complete fuel cell controller for the use in a vehicle (prototype).

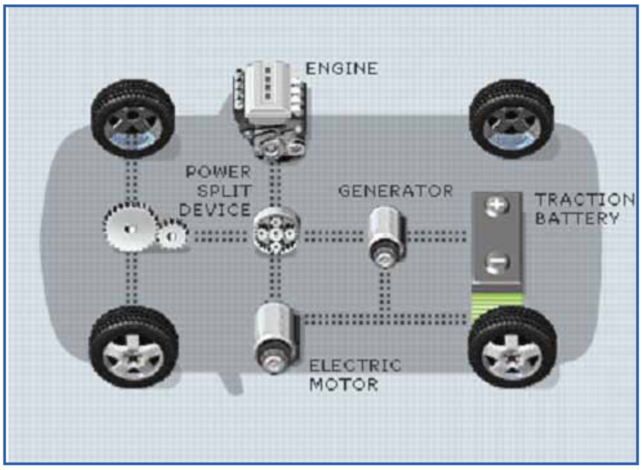
- **Solid Oxide Fuel Cells (SOFC).** SOFC have been modeled by using Diffpack, an object-oriented problem-solving environment for the numerical modeling and solution of partial differential equations of inuTech GmbH. The performed simulation on SOFC, undertaken by the Fraunhofer IKTS Dresden, showed that stack voltage and average Nernst potential are not sensitive to the gas distribution as long as the local fuel supply is adequate.

Thermal Management

Jet Engine Emissions

EnginSoft S.p.A. has participated in activities within EC-funded research projects on low emission like the ANTLE and CLEAN programmes for heat transfer and combustion optimization applications. In fact, such activities were among the first to employ the novel developed optimization platform modeFRONTIER in industrial applica-tions.

Nowadays EnginSoft is one of the 40 partners of NEWAC (New Aero Engine Core Concept), a project which aims at attaining the ACARE 2020 targets.



HEV with engine, electric motor, generator, battery and power

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Multidisciplinary design optimization in France

ESTECO France, recently renamed EnginSoft France represents a team of engineering and service experts dedicated to the promotion, support and training of optimization design tools in the Western European French speaking market.

In 2008, EnginSoft France, in collaboration with its partners, SIREHNA, TASS TNO Automotive France and CETIM, are hosting a series of Technology Days in Paris and throughout France and Belgium.

Results of robust design optimization with chaos collocation method

On March 20th, engineers of EnginSoft France presented modeFRONTIER version 4 to local customers in the company's new office in Paris, Boulogne Billancourt. The full day program covered the main new features of the latest release, such as Self Organizing Maps (SOM) which allow the user to analyze and organize data sets by highlighting the most important relationships between inputs and outputs. A detailed optimization example was presented to the attendees, as well as the new graphical interface, the optimization wizard, new algorithms and many more features available in modeFRONTIER v4.

28th March saw a Seminar dedicated to Passenger Safety and using modeFRONTIER for Madymo, the world's leading design and crash simulation software. Hosted by TASS TNO Automotive France and EnginSoft France, the seminar provided insights into Multidisciplinary Design Optimization with both technologies.

To hear more about the next planned events in France and Belgium, please contact:
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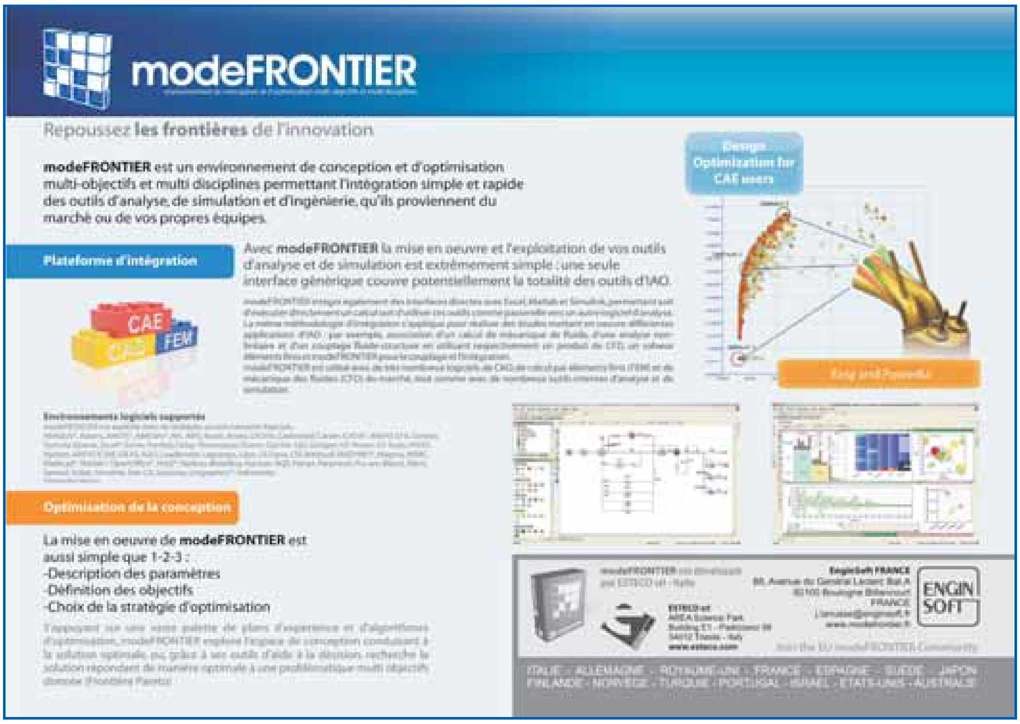
www.modefrontier.fr



March 2008 - modeFRONTIER v4 advertisement for France.

Advanced optimization studies at Istanbul Technical University

Since 2006, the Faculty of Aeronautics and Astronautics of Istanbul Technical University has applied modeFRONTIER in graduate level optimization classes, student projects and theses under the supervision of Assistant Professor Dr. Melike Nikbay. In spring 2007, and in this context, a modeFRONTIER seminar was organized and attended by 50 master and PhD students at the University.

The Faculty of Aeronautics and Astronautics has a great teaching and research potential with its advanced laboratories as Tri-sonic Research, Composites and Structures, Controls and Avionics, Computational Engineering, MDO, Space Systems Design and Test, Parallel Computation, Virtual Reality and Atmospheric Sciences.

The Faculty's current MDO research and teaching areas include, but are not limited to: Aeroelasticity and Aeroelastic Optimization, Structural Design and Optimization, CFD Based Design Optimization, Fluid-Structure Interaction Instabilities, Airplane Maintenance Optimization, Gradient-Based Numerical Optimization Algorithms, Reliability Based Design Optimization. Recently and again under the direction of Assistant Professor Dr. Melike Nikbay, the graduate students of MDO lab also invested great efforts in the successful coupling of modeFRONTIER with various engineering tools, such as: CATIA, Abaqus, FLUENT, Gambit and MPCCI for multi-disiplinary analysis. TUBITAK (The Scientific and Technological Research Council of Turkey) supports Prof. Nikbay's multidisciplinary aerospace research under the National Young Researcher Career Development Program of Turkey.

The advanced optimization studies of the Faculty and MDO lab which involve modeFRONTIER are strongly supported by ESTECO srl, the program developers, and FIGES A.S., EnginSoft's and ESTECO's much valued partner in Turkey. All parties involved are pleased with the collaboration in place and the results of the Faculty's research work achieved so far. The use of modeFRONTIER by Prof. Dr. Melike Nikbay, her team and students, is now documented in three papers which will be presented at two international conferences, and at an important event in Turkey this year:

I) Melike Nikbay, Arda Yanangonul, Levent Oncu, "Structural Optimization of an Aircraft Wing with Multi-objective Genetic Algorithms", HASEM'08 Kayseri VII. Aerospace Symposium, 15-16 May 2008, Kayseri, Turkey.

II) Melike Nikbay, Levent Oncu, Arda Yanangonul, "Multi-Objective and Gradient Based Structural Design Optimization of an Aircraft Wing", ASMDO Second International Conference on Multidisciplinary Design Optimization and Applications, 2-5 September 2008, Gijon, Spain.

III) Melike Nikbay, Levent Oncu, Ahmet Aysan, " A Multi-disciplinary Code Coupling Approach for Parallel Analysis and Optimization of Aeroelastic Systems", 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 10-12 Sep 2008, Victoria, British Columbia, Canada.

For more information, please contact:
Prof.Dr. Melike Nikbay,
nikbay@itu.edu.tr
Istanbul Technical University, Faculty of Aeronautics and Astronautics
www.figes.com.tr

FIGES CAD CAE

FIGES A.S. is EnginSoft's and ESTECO's partner for modeFRONTIER in Turkey

OZEN Engineering hosts Seminar in multi-objective design optimization in Silicon Valley

Since summer 2007, OZEN Engineering Inc. is EnginSoft's partner of choice for the promotion and distribution of modeFRONTIER in California.

Based in Sunnyvale, OZEN Engineering is a leader in the Silicon Valley and San Francisco Bay area in simulation technologies and finite element analysis. The OZEN team present a broad range of expertise in MEMS, Fracture Mechanics and Fatigue, Ball Grid Arrays (BGA's), Heat Transfer, Dynamics and CFD as well as Biomedical Analysis.

OZEN Engineering Inc. office in Sunnyvale, Silicon Valley

In recent years, OZEN Engineering Inc. has built core competences in the fields of Multi-objective Design Optimization, Robust Design, Design for Six Sigma (DFSS) and Process Integration (PI), technologies that leading scientists today regard as indispensable for the successful application of CAE simulation in the future.

On 26th & 27th February 2008, OZEN hosted a 2-day Seminar in Multi-objective Design Optimization of BGA Ball Grid Arrays, Packages for Reliability, in Sunnyvale, Silicon Valley, Northern California.

The Seminar attracted an audience of 35 participants that reflected the diversity of multi-objective design optimization, with a large number of representatives from the IT and semiconductor industries, e.g. Cisco Systems, Intel, SUN Microsystems. The academia of Silicon Valley was represented by several delegates from San Jose State University, the Mechanical and Aerospace Engineering Department, and the Director of the Electronics and Packaging Laboratory with two of his students.

One of the main objectives of the Seminar was to present an ongoing study about the multi-objective design optimization of BGA packages. The study puts particular emphasis on determining the critical input variables that a BGA designer may consider to improve the performance of his design with respect to reliability. In this context, the agenda of day 1 included topics, such as:

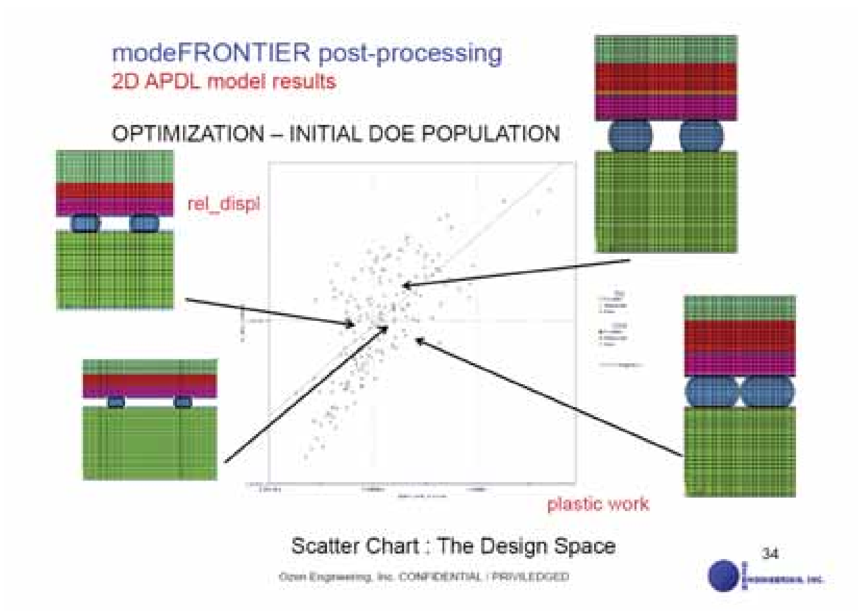
26th & 27th February - Seminar participants from industry and academia

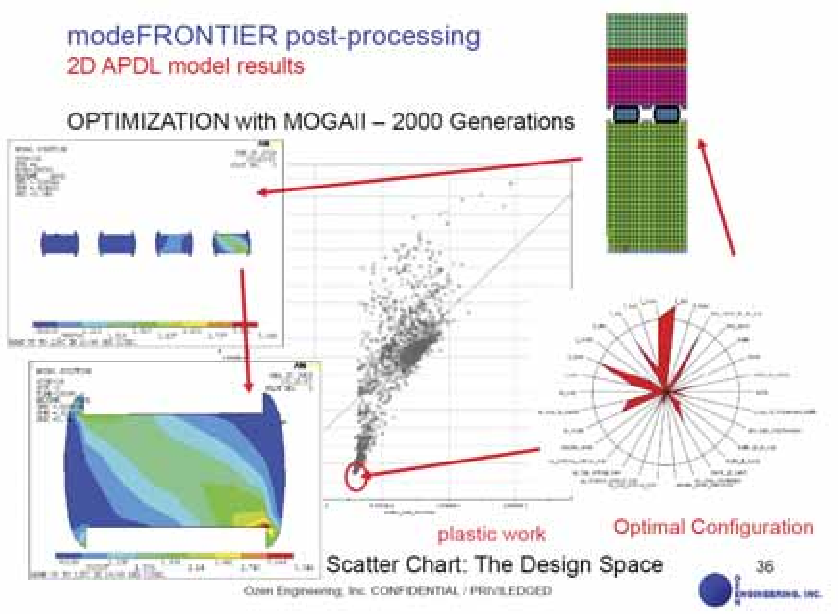
- 2D vs 3D approaches
- Modeling: ANSYS Classic vs Workbench
- Identification of geometric and material properties input variables
- Definition of output variables and objectives
- Set-up of the finite element models in ANSYS Classic and Workbench
- Set-up of the optimization problem in modeFRONTIER: the workflow
- Preliminary DOE analyses for identification of the most important

critical input variables

- Optimization with MOGA II for all analyses
- Generating Response Surfaces: comparisons of different response surfaces
- Determination of the optimal design: Pareto frontier
- Validation of the virtual design by means of real analyses
- 3D Model + underfill: 400 feasible designs resulting from MOGA II optimization; Pareto frontier and real optimum

Among the conclusions drawn, we should say that 2D approaches can be employed for preliminary optimization, whereas refined optimization requires 3D approaches. Also, material thermal properties, in particular CTE, play an important role in the optimization of BGAs. Ball pitch is the critical geometric parameter, directly correlated to both objectives. The impact of underfill presence is extremely significant as far as the main objective is concerned. Further investigations and studies are needed to complete the study.





modeFRONTIER post-processing

Day 2 saw an introduction to modeFRONTIER presented by Nader Fateh, VP of ESTECO North America Inc. on behalf of the product developers and producers, ESTECO srl Trieste. Nader's introduction was followed and completed by a full class which provided the attendees with the knowledge needed in fundamental and advanced optimization technologies, in order to use modeFRONTIER effectively in their daily working environment.

The seminar concluded with a hands-on integration of ANSYS products and modeFRONTIER as well as modeling of BGAs, demonstrating assumptions and various modeling techniques.

The seminar and related discussions generated extensive interest among the attendees. Areas of particular interest were, for example, the interfacing of modeFRONTIER with other CAE/CAD /FEA/CFD tools, response surface generation in modeFRONTIER, the modeFRONTIER University Program to support the academia, or the use of the program to interpret experiments and experimental data.

Given the strong response to its invitation and the extremely positive feedback from the attendees during and after the training, OZEN Engineering Inc. is determined to further explore the market for optimization techniques in California. We also look forward to hosting the next seminars in the months ahead, in collaboration with ESTECO North America and EnginSoft S.p.A.

For further information, please contact:
OZEN Engineering Inc.
Alberto Bassanese,
Alberto.Bassanese@ozeninc.com
www.ozeninc.com

modeFRONTIER at SAE 2008 World Congress. The Premier Automotive Technology Event

14-17 April • Cobo Center • Detroit, Michigan, USA

The SAE World Congress 2008, the biggest event in automotive engineering worldwide, saw several papers that directly referenced modeFRONTIER.
Already when searching the Congress website http://www.sae.org/congress in advance, the number of contributions that involved modeFRONTIER reflected on the importance of the technology as one of the major optimization and process integration tools in automotive engineering.

The following four summaries should provide an initial insight into the topics and applications with which ESTECO was directly involved in or which were personally presented by the ESTECO team in Detroit during SAE.

In addition to these papers, and while visiting the technical Congress Sessions, everybody at ESTECO was pleased to learn about the results obtained by modeFRONTIER users when listening to their presentations highlighting the use of the software in various applications.

Paper Number 2008-01-0874

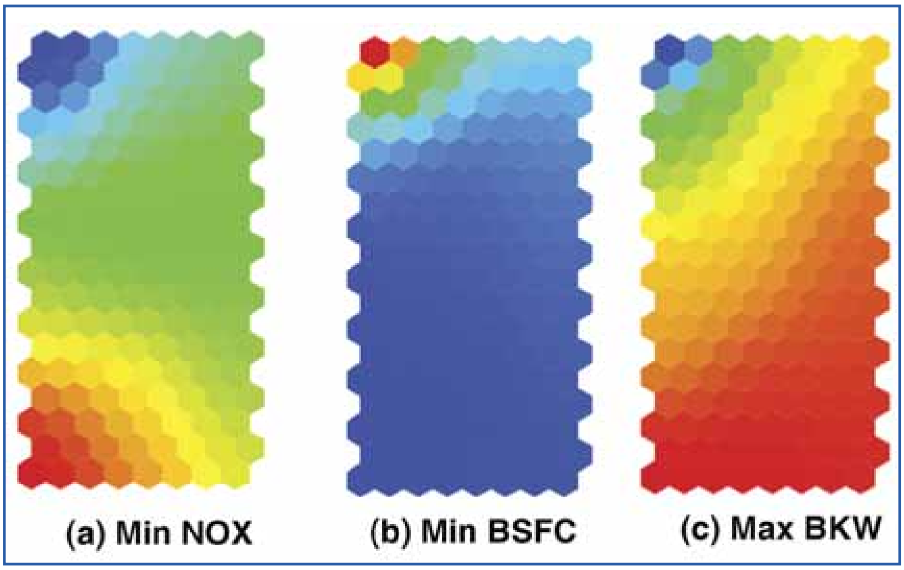
Self Organizing Maps (SOM) for Design Selection in Multi-Objective Optimization using modeFRONTIER

Sumeet Parashar, Nader Fateh
ESTECO North America Inc., Livonia, MI
Valentino Pediroda, Carlo Poloni
University of Trieste, Trieste, Italy

ABSTRACT
Self Organizing Maps (SOM) have evolved as a very useful visualization and data analysis tool for high dimensional data. Visualization and analysis of Pareto data for multi-objective optimization problems with more than three objectives is also a challenge. This paper investigates the application of SOM for visualization and design selection for multi-objective Pareto data.

The SOM is applied to investigate the spread of Pareto front as well as to investigate trade-offs between objectives.

The visualization and selection strategy is applied to mathematical test problems to explain the concept. Later, it is also applied to real world automotive design problems of engine optimization.



Component maps for engine design test problem

Paper Number 2008-01-1429

Efficient Stochastic Optimization using Chaos Collocation. Method with modeFRONTIER

Valentino Pediroda, Lucia Parussini, Carlo Poloni - University of Trieste, Italy
Sumeet Parashar, Nader Fateh
ESTECO North America Inc, Livonia, MI
Mauro Poian - ESTECO srl, Trieste, Italy

ABSTRACT
Robust Design Optimization (RDO) using traditional approaches, such as Monte Carlo (MC) sampling requires tremendous computational expense.
Performing a RDO for problems involving time consuming CAE analysis may not even be possible within time constraints.

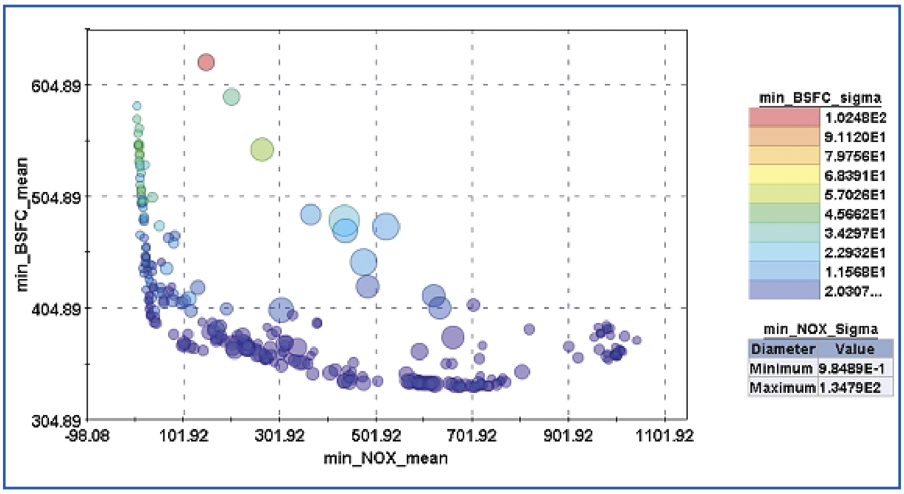
In this paper, a new stochastic modeling technique based on a chaos collocation method is used to measure the mean and standard deviation ( ) for uncertain output parameters. For a given accuracy, the chaos collocation method requires far less sample evaluations compared to MC.

The efficient evaluation of mean and std. deviation terms using a chaos collocation method makes it quite attractive to be used with RDO methods. In this work, the RDO of an automotive engine design is performed employing a chaos collocation method. The solution strategy is implemented into the commercial Process Integration and Design Optimization (PIDO) software tool modeFRONTIER. modeFRONTIER provides a very effective environment to apply multi-objective optimization algorithms to various CAE or in-house analyses and simulation tools. The engine design simulations were performed using GT-Power through modeFRONTIER. The chaos collocation method is coded in MATLAB scripts that are also invoked through modeFRONTIER. The rest of the paper covers an introduction describing the motivation and challenges. The chaos collocation method is described followed by a description of its application through modeFRONTIER. The engine design optimization problem is explained followed by a discussion of the RDO results.

Paper Number 2008-01-0871

Game Theory Approach to Engine Performance Optimization

Nader Fateh, Sumeet Parashar
ESTECO North America Inc., Livonia, MI
John Silvestri
Gamma Technologies Inc., Westmont, IL



Results of robust design optimization with chaos collocation method

ABSTRACT
Genetic Algorithms have proved to be very useful as global search methods for multi-dimensional optimization problems. One drawback, however, is that they are inefficient from the point of view of the number of function evaluations. This paper presents a two phase approach to optimization using Game Theory in an initial step which provides a family of designs that are close to the Pareto frontier. The starting population for the genetic algorithm is then selected from the non-dominated designs produced in the first phase. This ensures that the genetic algorithm starts with a population of points which are already optimized to a large degree.

Paper Number 2008-01-0886

Multi-objective Optimization of a Charge Air Cooler using modeFRONTIER

Phil Stephenson, Yang Chen
BEHR America Inc., Troy, MI
Nader Fateh, Sumeet Parashar
ESTECO North America Inc., Livonia, MI
Mauro Poian - ESTECO srl, Trieste, Italy

ABSTRACT
In order for an automotive charge air cooler (CAC) to function efficiently, the flow of air through the cross tubes should be as uniform as possible. The position of the inlet and outlet, as well as the shape of the header tanks, are generally the most important determinants of the flow uniformity, and therefore of the cooling performance of the system. In an attempt to achieve this goal of flow uniformity, however, the effect on pressure loss in the system must also be considered. Further, the cost of the CAC tanks, which is directly related to the amount of material, should be minimized.

Finally, the physical space in which the CAC can be located is limited by other underhood components and vehicle styling features. This presents an optimization problem with four conflicting objectives:

- to reduce the pressure loss in the system,
- to increase the uniformity of flow in the tubes,
- to minimize the tank material and
- to conform to the package volume.

In this work, CATIA v5 was used to define the package volume to which the optimized CAC must conform. Also, a commercial CFD tool was used to create the geometry and mesh, and to run the analysis; modeFRONTIER was used as the multi-objective optimization tool to automatically drive the process of

modifying the parameters controlling the shape of the tanks, and position of the inlet and outlet, in order to achieve the above objectives.

If you are interested in one or more of the above topics, please contact:
ESTECO srl Headquarters at:
sales@esteco.com

List of Papers presented at SAE2008 Technical Sessions containing modeFRONTIER as a keyword:

1. 2008-01-1429: Efficient Stochastic Optimization Using Chaos Collocation Method with modeFRONTIER 04/14/2008. Author(s): Valention Pediroda, Sumeet S. Parashar, Carlo Poloni, Mauro Poian, Nader Fateh, Lucia Parussini
2. 2008-01-0886: Multi-Objective Optimization of a Charge Air Cooler using modeFRONTIER and Computational Fluid Dynamics 04/14/2008 Author(s): Philip W. Stephenson
3. 2008-01-0713: Multiple Regression Analysis of OSC Characteristics Under Transient TWC Conditions 04/14/2008. Paper Author(s): Takashi Yamada, Makoto Nagata, Hiroki Ashizawa
4. 2008-01-0219: Multi-Objective and Robust Design Optimization Techniques applied to Engine Component Design 04/14/2008. Author(s): Walter Zottin, Rodrigo Silva, Marcus Reis, Ana Cuco
5. 2008-01-0874: Self Organizing Maps (SOM) for Design Selection in Multi-Disciplinary Multi-Objective Optimization 04/14/2008. Author(s): Sumeet S. Parashar
6. 2008-01-1356: A Parametric Optimization Study of a Hydraulic Valve Actuation System 04/14/2008. Author(s): Francesco Mariani, Michele Battistoni, Luigi Foschini, Marcello Cristiani
7. 2008-01-0949: Assessment of Optimization Methodologies to Study the Effects of Bowl Geometry, Spray Targeting and Swirl Ratio for a Heavy-Duty Diesel Engine Operated at High-load 04/14/2008. Author(s): Yu Shi, Rolf Reitz
8. 2008-01-0832: Integrated Development and Validation of HVAC Modules Using a Combined Simulation and Testing Approach 04/14/2008. Author(s): Yang Chen

ESTECO Frankfurt Francesco Linares appointed Technical Manager

Since the beginning of the year 2008, Francesco Linares who holds a Master of Science in Engineering und a Master in CFD Computational Fluid Dynamics, is the Technical Manager of ESTECO Frankfurt.

With the objective to support ESTECO GmbH and modeFRONTIER in Germany, Austria and Switzerland and to advance his professional career, Francesco Linares has transferred his residence from Padova, Italy to Frankfurt am Main a few months ago.

Prior to joining ESTECO Frankfurt, Francesco has been with EnginSoft S.p.A., the ANSYS Reseller and leading CAE service provider in Italy.

Francesco has extensive experience in the fields of simulation and optimization. In recent years, he has significantly contributed to the success of various projects and developments in these and other areas.

Francesco's focus has always been modeFRONTIER and to support companies in the application of the software thus achieving savings in time, money and resources by using state-of-the-art technologies for process integration and optimization.

Francesco has supported ESTECO Frankfurt and its customers with his strong commitment and expertise since January. During this relatively short time, Francesco was able to contribute significantly to the success of various product presentations and to the efficiency of modeFRONTIER technical support.

With Francesco's precious input and technical background, ESTECO GmbH succeeded in acquiring Sulzer Pumps in Switzerland as a customer and in starting a project of larger scale with ABB Switzerland. For more and up-to-date information about ESTECO GmbH, please visit our website http://www.esteco.de and learn about:

- modeFRONTIER in Germany, Austria and Switzerland and related product new
- Application examples and case studies which can be viewed and/or downloaded
- Events where modeFRONTIER and our experts will be present
- Free Workshops and how to register online
- The company's history, background and our team

ESTECO GmbH Frankfurt
Sybille Arthen – arthen@esteco.de
Andrea Hauschopp – hauschopp@esteco.de

EnginSoft and TCN Consortium sponsor NAFEMS by offering Courses on Computational Technologies at discounted fees

At its recent General Assembly Meeting, the NAFEMS Italy Steering Committee, EnginSoft and TCN agreed that Members of NAFEMS will receive a discount on the wide range of Courses on Computational Technologies offered by TCN and EnginSoft. Thus, an initiative that was very well accepted by the NAFEMS Community and highly successful in past years, was re-launched in February 2008

Already in 1998, EnginSoft in its role as a founder member of TCN and NAFEMS Italy, encouraged the NAFEMS Community to benefit from TCN Training by offering the program modules at discounted fees to the Members of NAFEMS. This initiative soon became a success in Italy and today reaches Members all over Europe, bringing together specialists, users and anyone interested in engineering analysis and simulation.

EnginSoft is a consulting company operating in the field of Computer-Aided-Engineering (CAE), virtual prototyping, process simulation and, more generally, scientific IT targeted to the optimization of design and production processes.

Founded in 1984, EnginSoft today has over 80 employees and 5 bases in Italy. We support partner offices in various parts of Europe and North America and promote the European modeFRONTIER™ Network whose primary goal is to help customers and prospects to broaden their knowledge in the modeFRONTIER™ Technology.

EnginSoft maintains numerous partnerships with both companies and universities on a European level and is currently involved in and supports nine EU Research Projects: NADIA, AutoSim, ESoCAET, EUA4X, IDEAL, FENET, METRO, NUFRIC, ReadOut.

EnginSoft's mission is to spread the culture of digital technologies to both production and research fields. We pursue this challenge by offering engineering consultancy services, a range of world-class CAE software, dedicated training courses and by promoting conferences, collaborations with research institutes, and publishing activity.
www.enginsoft.net

EnginSoft and TCN offer specific courses dedicated to MDO (Multi-Disciplinary Optimization) and PIDO (Process Integration and Multi-Objective Design Optimization). These courses encompass the groups' expertise in these areas and specifically in modeFRONTIER™, the multi-objective optimization and design environment software. Developed and produced by ESTECO srl, modeFRONTIER™ is a state-of-the-art PIDO tool, written to allow easy coupling to almost any computer-aided-engineering (CAE) tool.
www.modefrontier.com

Founded in 2001, TCN Consortium is a Centre for Higher Training in Computational Technologies. Its main objective is to promote training activities related to:

- CAE (Computer Aided Engineering)
- Virtual prototyping and testing
- Numerical simulations
- iDP (Intelligent Digital Prototyping)

and linked disciplines dedicated to statistics, data structure, Information Technology and software engineering in general.

Conducted in English language and mostly held in Italy, TCN Courses aim at enabling engineers in industry and academia to use software technologies in the context of current requirements in production and development. TCN's training offer comprises a series of short courses on numerous subjects, such as:

- Acoustics
- CFD
- Composite materials
- Computer science
- Electromagnetism
- FEM
- Material science and structural integrity
- Microsystems
- Multi-body systems
- Numerical Calculations
- Statistics and other decision-making tools
- and more

In addition, the TCN Consortium approaches the international learning community with a knowledge network that includes as well:

- Masters particularly focused on the application of current software technologies for numerical simulation
- Minimasters in Mechatronics
- Fellowships offered to young researchers in the frame of EUA4X – the European Atelier for Engineering and Computational Science
- Distance learning, organization and standardization of didactic material
- Web-based courses, such as METRO (MEtallurgic TRaining On-line)
- Tailor-made training activities for industry
- Initiatives linked to further EU-funded projects, such as ESoCAET (European School of Computer Aided Engineering Technology) and ILTOF (Innovative Learning and Training On Fracture)

For more information and details on TCN Consortium training, please visit: http://www.consorziotcn.it/eng/
and contact:

TCN Consortium Secretary's Office
Mirella Prestini - info@consorziotcn.it
EnginSoft Marketing Europe
Barbara Leichtenstern
info@enginsoft.it

modeFRONTIER Event Calendar

Germany

09-13 June - ASME Turbo Expo 2008. ESTREL Hotel Berlin and Convention Center, Berlin. Come and visit the EnginSoft booth #918!

10 June: 15.00-15.45 modeFRONTIER Stage Presentation in the exhibition grounds: Aero-Engine components design - CFD optimization via modeFRONTIER, L. Bucchieri, EnginSoft www.turboexpo.org

UK

5-6 June - ANSYS European Built Environment CAE Conference EBECC - London. SWS Engineering and EnginSoft presenting: The Brenner Pass Tunnel, the design of Europe's longest railway tunnel. http://www.ansys.com/events/ebecc/index.htm

10-11 June - NAFEMS UK Conference 2008
Paramount Cheltenham Park Hotel, Cheltenham, East Midlands. Meet us at the ICON booth! Luca Fuligno, EnginSoft, presenting: Integrating simulation tools during the design process: A good way to head towards true multi-disciplinary optimization: http://www.nafems.org/events/nafems/2008/UK/

Ireland

19-20 June - modeFRONTIER Training Course for Academic Specialists. Trinity College Dublin. For more information please contact Dr. Cristina Ancona (c.ancona@enginsoft.it).

France and Belgium

EnginSoft France 2008 Journées porte ouverte. Dans nos locaux à Paris et dans d'autres villes de France et de Belgique, en collaboration avec nos partenaires, TASS TNO Automotive France et CETIM.
Veuillez contacter Jocelyn Lanusse, j.lanusse@enginsoft.fr, pour plus d'information, http://www.modefrontier.fr/

21-22 October- modeFRONTIER Training Course for Academic Specialists. Von Karman Institute - Rhode Saint Genèse (Belgium). For more information please contact Dr. Cristina Ancona (c.ancona@enginsoft.it).

Italy

5-6 June - modeFRONTIER Training Course for Academic Specialists. ESTECO srl Headquarters, Trieste
Please note: These Courses are for Academic users only. The Courses provide Academic Specialists with the fastest route to being fully proficient and productive in the use of modeFRONTIER for their research activities. The courses combine modeFRONTIER Fundamentals and Advanced Optimization Techniques. For more information, please contact Dr. Cristina Ancona at c.ancona@enginsoft.it

30 June-4 July – ECOMMAS 2008, 5th European Congress on Computational Methods in Applied Sciences and Engineering
Presentations by ESTECO srl:

- Radial Basis Functions Performance on Large Scale Problems. By Enrico Rigoni and Alberto Lovison
- Bounding the Archive Size in Multi-objective Optimization. By Danilo Di Stefano and Silvia Poles
- A genetic algorithm approach for the detection of corrosion in large-scale structures. By G. Deolmi, F. Marcuzzi, Silvia Poles and S. Marinetti
- modeFRONTIER framework and its uncertainty capabilities in Aeronautics. By Carlo Poloni

http://www.iacm-eccomascongress2008.org

14-15 October - modeFRONTIER International Users' Meeting 2008. Stazione Marittima, Trieste. Stay tuned to www.esteco.com for more information to appear soon.

Extend your stay and move on to nearby Venice for:
16-17 October - TCN CAE 2008 International Conference on Simulation Based Engineering Hotel Laguna Palace di Mestre, Venice. TCN CAE 2008 provides the international forum for researchers, scientists, engineers, managers dedicated to the fields of applied computational science and engineering. TCN

CAE 2008 promotes scientific knowledge and its incorporation into simulation-based engineering through computer simulation.

Be part of TCN CAE 2008, submit your abstract today and/or check out opportunities for exhibitors:
http://tcncae08.consorziotcn.it

On the same days, and at the same venue, visit the:
EnginSoft Conference 2008
The largest CAE event in Italy, will host the Italian modeFRONTIER Users' Meeting, with large accompanying exhibition featuring latest software and hardware products and vendors from around the world.
http://meeting2008.enginsoft.it/

22-23 September - modeFRONTIER Training Course for Academic Specialists. Politecnico di Milano. For more information please contact Dr. Cristina Ancona (c.ancona@enginsoft.it).

24-25 November - modeFRONTIER Training Course for Academic Specialists. ESTECO srl Headquarters, Trieste. For more information please contact Dr. Cristina Ancona (c.ancona@enginsoft.it).

USA

14-17 April - SAE 2008 World Congress. Cobo Center, Detroit, Michigan. ESTECO & ESTECO North America and modeFRONTIER users presenting various applications, e.g.

- Self Organizing Maps (SOM) for Design Selection in Multi-objective Optimization using modeFRONTIER
- Efficient Stochastic Optimization using Chaos Collocation Method with modeFRONTIER
- Game Theory Approach to Engine Performance Optimization
- Multi-objective Optimization of a Charge Air Cooler using modeFRONTIER

Please contact Nader Fateh, nader.fateh@esteco.com, for more information. http://www.sae.org/congress

20-22 May - iMUG08 Moldflow Conference
Meet our experts at the booth of ESTECO North America!
Luca Fuligno, EnginSoft, presenting on: Optimizing an automotive component warpage acting on its ain shape and process parameters – see Conference Program!
www.moldflow.com/imug08

Greece

08 May - 2nd PhilonNet Conference. Athens. PhilonNet presenting CAE Technologies in Greece. The Conference Program will span topics related to the application of ANSYS, LS-DYNA, Moldflow and modeFRONTIER.
http://www.philonnet.gr

Turkey

15-16 May - HASEM'08 Kayseri VII. Aerospace Symposium Kayseri. Presentation: Structural Optimization of an Aircraft Wing with Multi-objective Genetic Algorithms
by Melike Nikbay, Arda Yanangonul, Levent Oncu,
Istanbul Technical University, Faculty of Aerospace and Astronautics. For more information, please contact Melike Nikbay, nikbay@itu.edu.tr

Spain

2-5 September - Second International Conference on Multidisciplinary Design Optimization and Applications Gijon. Visit us at the booth of APERIO Engineering Technology!
Presentations:

- Application of Game Strategy in Multi-Objective Robust Design Optimization: Applications to Aerodynamic, Structural and System Simulations. By Carlo Poloni - Università di Trieste, Dipartimento di Ingegneria Meccanica, Paolo Geremia - ESTECO srl, Trieste, Luca Fuligno - EnginSoft SpA, Trento
- Multi-Objective and Gradient Based Structural Design Optimization of an Aircraft Wing. By Melike Nikbay, Levent Oncu, Arda Yanangonul, Istanbul Technical University, Faculty of Aerospace and Astronautics
  www.asmdo.com/conference2008

Canada

10-12 Sep 2008 - 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. Fairmont Empress Hotel and Victoria Conference Centre, Victoria, British Columbia

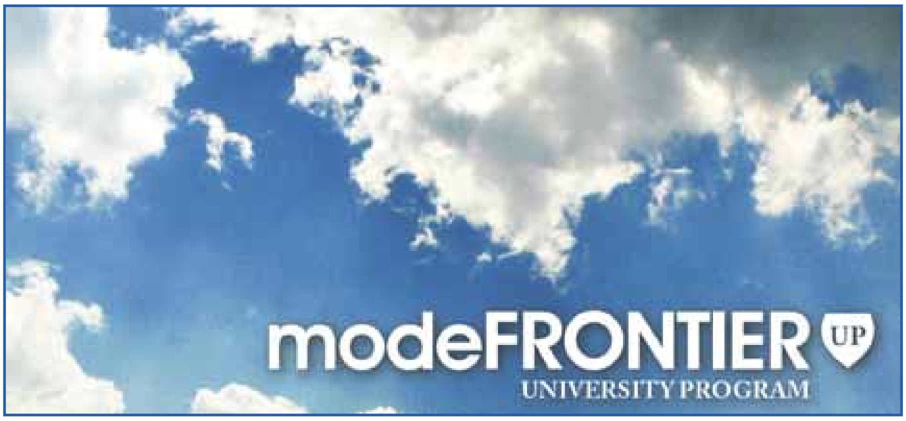
Presentation: A Multi-disciplinary Code Coupling Approach for Parallel Analysis and Optimization of Aeroelastic Systems by Melike Nikbay, Levent Oncu, Ahmet Aysan

Istanbul Technical University, Faculty of Aerospace and Astronautics. www.aiaa.org/events/mao/

For more information:
info@modefrontier.eu

The modeFRONTIER University Program

We believe that the future of optimization tools begins in academia, where research continues to expand our understanding of numerical methods, physical models, and computing technology.



The modeFRONTIER University Program is a joint initiative of EnginSoft and ESTECO which aims at fostering strong ties with universities and working in close collaboration with research institutes and academic organizations.

Through the modeFRONTIER University Program, we support education with specific initiatives to facilitate teaching and research related activities on campuses across the world.

Training courses for academic specialists

Since November 2007, regular free training courses specifically dedicated to the academic community are being hosted by EnginSoft and ESTECO in Italy, and very soon also at other European locations that are easy accessible.

modeFRONTIER at the Vehicle Safety Institute

The following testimonial and picture of a workflow has been provided by courtesy of Gregor Gstrein, of the Vehicle Safety Institute (VSI) of Technical University of Graz, Austria, who attended our recent training course in Bergamo.

January 2008 - Course participants at ESTECO Headquarters in Trieste.. More than 100 professors, researchers and PhDs from all over Europe are currently testing modeFRONTIER on their own research applications after attending dedicated training courses.

Application of modeFRONTIER in the development of restraint systems:

The Vehicle Safety Institute (VSI) was founded in 2002 as a working group of the mechanics department. In the year 2006, it moved into a totally new building with a generously spaced, fully equipped test-lab. For different demands, there now exists the possibility to perform component-tests or even full scale crash-tests.

About 20 employees are working in different research fields:

- Accident research
- Active and passive safety
- Safety of roadside infrastructure
- Biomechanics

One PhD-project at the VSI addresses the development of restraint systems in passenger cars. It consists mainly in simulation-work combined with evaluation tests at the end of the project. The large number of input parameters in this topic causes numerous possible solutions. For a single-minded, fast development it is necessary to apply optimization tools or at least an automated simulation, such as modeFRONTIER. The meaningful degree of automation depends a lot on the knowledge of the technical problem and the purpose of the research. So, for the first step it seems to be reasonable to apply a DOE over the whole area of variation. Afterwards, when we know better how specific output-parameters behave against the input-parameters, it is possible to narrow down the area where to search for a good solution. Following these ideas, the number of simulations is minimized as well as the risk for getting senseless solutions.

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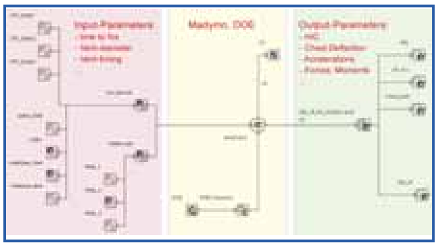
The training courses for academic specialists provide users with the fastest route to being fully proficient and productive in the use of modeFRONTIER for their research activities. The courses combine modeFRONTIER Fundamentals and Advanced Optimization Techniques.

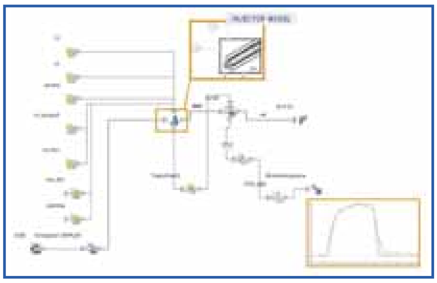


Workflow simulations with modeFRONTIER at the Vehicle Safety Institute – VSI

Conducted in English language and with no prerequisites required, the training courses aim to reach a European academic and research audience with various technical backgrounds.
The following testimonial has been kindly provided by Professor Piero Pelloni and Professor Gian Marco Bianchi of DIEM, the Department of Mechanical Engineering of University of Bologna.

Multi-objective optimization enters the DIEM research group

The use of modeFRONTIER at the Department of Mechanical Engineering (DIEM) of University of Bologna is becoming mandatory in the new scenario of simulation and design. A research group, lead by Professor Pelloni and coordinated by Professor Bianchi, is involved in the development and application of methodologies for the simulation of internal combustion engines and fluid-power components and systems. A permanent staff of four people, together with seven engineers, works on advanced CFD projects (LES, Multi-phase flow, etc.) and know-how transfer to companies, such as Piaggio & C., Moto GP and F1 teams, among others. DIEM is faced with new challenges in design and modelling which require to conceive and use tools able to predict component and system behaviour when few data are available, i.e."Modelling the unknown". The approach to modeFRONTIER through a basic training course has allowed the concept of multi-objective optimization to enter the DIEM research group. The two days training class provided effective information on the modeFRONTIER tools and their applications, thus shortening the start-up phase. After the training class, a test case focused on a black-box injector model was chosen as first application. DIEM developed an hydraulic simple injector model for high pressure



modeFRONTIER-AMESim coupled simulation for training the hydraulic simple injector model for high pressure injection systems developed by DIEM

injection systems (C.R. and GDI) using the AMESim code. Injector design specifications, unavoidable to reproduce the injector's hydraulic behaviour, are rarely (or costly) available to end users, such as engine manufacturers and research centres. The application of a coupled simulation using modeFRONTIER-AMESim has been revealed to be successful for this goal. After a short training (optimization), the black-box injector model can reproduce the behaviour of a generic multi-hole injector without needing information about its design and manufacturing. Very few experimental points have been demonstrated to be necessary to make the model capable to reproduce the actual injector over the whole range of operating conditions within a given accuracy.

This is only a first and simple example of the benefits achieved by using optimization strategy with the perspective to extend the application of modeFRONTIER to other projects currently performed at DIEM.

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Regular training courses will be held in 2008, at alternating locations in Europe. If you are interested in attending or hosting trainings, please contact us to hear about the next planned dates and venues for academic training.

Additional features

The modeFRONTIER University Program comprises as well a complete offer for PHD License, Consultancy License and Technical Support. Additionally, our proposal includes:

For Teachers and Researchers

- Visibility of academic research activities to the scientific community through the publication of papers in international magazines and on web pages as well as participation at conferences and annual users' meetings
- Through the TCN consortium and the e-learning portal, professors and researchers can teach their courses to an audience of professional and edit their works www.consorziotcn.it www.improve.it

Partnerships

- Partnership in European co-funded projects
- Sponsorship and attendance at your scientific conferences
- Organization of academic seminars on optimization

For Students

- modeFRONTIER training courses for students and funding of thesis projects

Contacts

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TCN CAE 2008

International Conference on Simulation Based Engineering and Sciences

Venice, Italy, 16-17 October 2008

http://tcncae08.consorziotcn.it

TCN CAE 2008 will provide an international forum for researchers, scientists, engineers, managers dedicated to the fields of applied computational science and engineering. The Conference will bring together the industrial and scientific worlds of simulation, thus promoting latest advancements in a technology sector that various independent studies regard as indispensable for achieving progress in engineering and science in the 21st century.

TCN has placed greatest emphasis on the Conference structure and themes. The ultimate goal is, of course, to meet the expectations of delegates from science and industry, but also to allow for best possible interaction and exchange between the two worlds.

The opening plenary session on Thursday reflects the four pillars of TCN and the conference: Academia - Industry - Research - Software. Four eminently respectable speakers will inspire the audience by highlighting unique perspectives.

The afternoon program will be dedicated to Simulation-based Science with four parallel sessions focusing on the key areas of:

- Medicine (Computational Bioengineering, Biomechanics, Biomedical)
- Materials (Multi-scale approaches)
- MDO, Robust Design & Decision Making
- Education and Knowledge transfer in Computational Science and Engineering

Friday's Program will feature Simulation-based Engineering, in particular multi-disciplinary approaches, in the four main industries of:

- Automotive
- Aerospace
- Power Energy (Oil & Gas, ….)
- Process & Manufacturing

While each session is dedicated to a specific industry, the program will strike a balance between industrial applications and research. Key issues, such as advances in numerical methods, software developments, the limits of current technologies, next generation algorithms, computational performance, necessary developments and future challenges will be discussed.