INCOSE Italian Chapter Conference on Systems Engineering (CIISE2014)
Rome, Italy, November 24 – 25, 2014

System Models Simulation Process Manangement and Collaborative Multidisciplinary Optimization

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Abstract.

Design optimization is a key activity to improve product performance in the design of modern manufacturing products, in order to reduce costs and time to market. Design optimization makes extensive use of virtual prototype simulations in the automatic search of the design space. Nowadays, engineering products draw together many components assembled in subsystems and systems. Each component is described by different physics, and the performance assessment covers the whole range of engineering analysis - e.g. mechanical, structural, thermal, electromagnetic, etc.-, requiring multiple simulation processes.

Many groups are involved in providing these different components and the simulation of physics dimensions are carried out by each single player counting on disparate levels of expertise and computing resources.

This paper shows how SOMO collaborative and distributed execution framework is used to compose multiple simulation processes at component level to generate system models managing the complexity of running multidisciplinary design projects. Driving process, component and subsystem knowledge with system models, SOMO allows a larger inference space for design, the ability to continually connect at the system level, and a basis for knowledge capture.

In this paper a real test case performed on the design and optimization of wind turbine is presented. The design workflow is managed by different engineering experts through a collaborative framework.

L’ottimizzazione, all’interno della progettazione di moderni sistemi, è un’attività fondamentale per migliorarne le prestazioni e ridurre i costi e il tempo per arrivare al prodotto finito. L’ottimizzazione numerica fa uso in maniera estensiva di simulazioni virtuali nella ricerca automatica all’interno dello spazio delle variabili. Oramai, prodotti ingegneristici sono composti da molti componenti che possono venir assemblati in sistemi e sotto sistemi. Ogni componente viene descritto attraverso diversi modelli fisici che richiedono diversi tipi di analisi e processi di simulazione, per coprire tutto l’intervallo di analisi ingegneristiche, meccaniche, termiche elettromagnetiche, per esempio.

I diversi gruppi sono coinvolti attivamente nel provvedere i diversi componenti e successivamente le simulazioni delle diverse grandezze fisiche vengono eseguite da ciascun progettista contando su diversi livelli di esperienza e risorse computazionali.

In questo articolo viene mostrato come la struttura collaborativa e distribuita di SOMO viene usata per costruire molteplici processi a livello dei componenti, utilizzati per generare modelli di sistema, gestendo la complessità di eseguire progetti multi disciplinari. Lo scambio di informazioni tra processi, componenti e sotto sistemi all'interno del modello di sistema, gestito attraverso SOMO, garantisce completa condivisione dello spazio delle variabili, l'abilità di interfacciarsi continuamente a livello di sistema e la basi per la condivisione della conoscenza.

In questo articolo, inoltre viene presentato un caso reale della progettazione e ottimizzazione di una turbina eolica. Il processo di progettazione viene gestito da i diversi esperti attraverso la struttura collaborativa.

Model Based Design Process and Collaborative MultiDisciplinary Optimization

System models incorporate vertically subsystems and components and integrate across different domains. They should have the ability to evaluate trade-offs of key attribute physics and control schemes, and need to be accessible to a range of end-users identified as simulation experts, optimization/design experts, data analysts and managers.

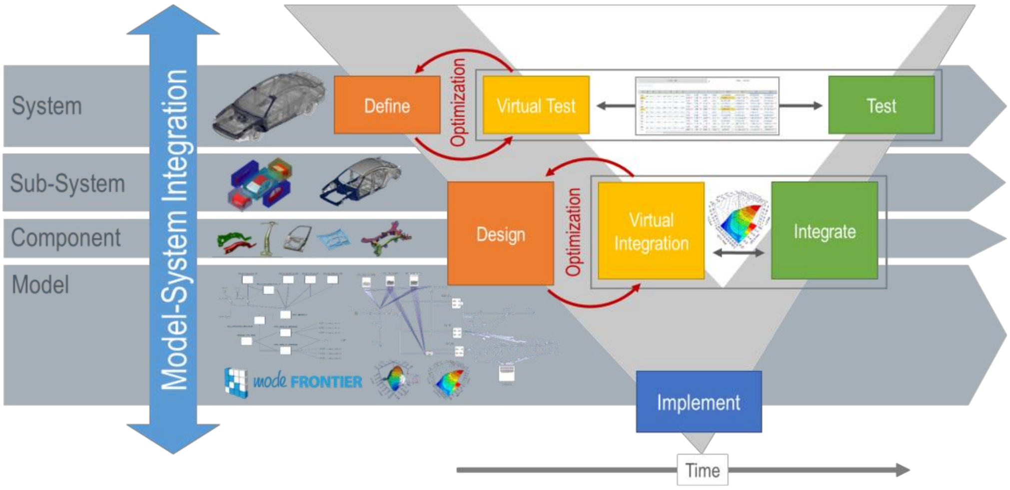

Figure 1. Model Based Design Process and Integration

System models use the data coming from the simulations of a component to evaluate the efficiency of the system in the whole range of conditions. Subsystems and component processes and knowledge can be transferred with minimal conversion from attribute owners, CAE, Test, Procurement, etc.

In the case presented here the partners successfully cope with a complex design scenario and effectively collaborate providing models, processes and resources.

At architectural or logical level, teams of system architects, along with domain experts, use model simulations to explore options for implementing the system architecture and optimize it. Each team can operate in parallel exploring different aspects of the architecture while feeding into and testing against a cohesive complete system model.

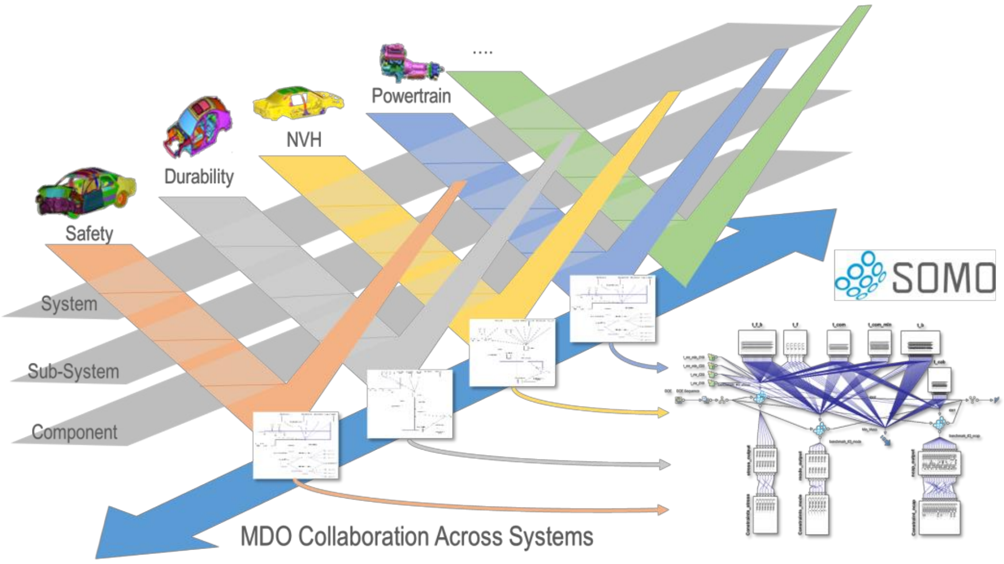

Figure 2. MDO Collaboration Across Systems

Thanks to the web interface and the collaborative environment for simulation process and data management, SOMO speeds up the communications among the teams, enforces standardization and the formalization of simulation processes, allowing the complete traceability of specific versions of data items and the processes/methods used for their creation from initial geometry to final results. Different teams start to create more detailed models that are more domain-specific (Safety, NVH, Durability, Powertrain, etc.) but remain able at the same time to verify them against a cohesive virtual view of the system that is revision controlled.

This framework promotes knowledge reuse and facilitates the sharing of core resources ranging from licensed software to computing power. By combining multiple models and levels of abstraction (from direct CAE models to Response Surfaces Methamodels), it provides a way to exercise and optimise the behaviour of a design at a functional, architectural, or fully implemented level of abstraction; or at a combination of these levels. In parallel with product design, the verification group is also designing and developing their physical verification tests against the virtual platform. This test set can run on the system model at any time during the development, to compare and validate virtual models.

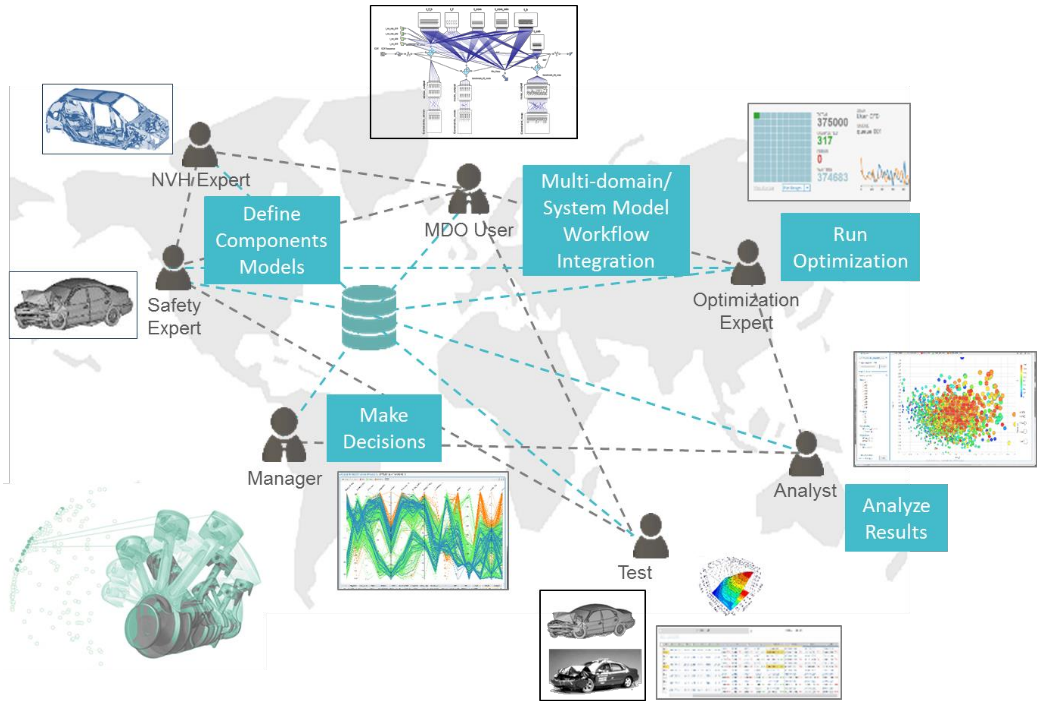

Figure 3. Collaborative simulation and Optimization Framework, SOMO.

Each collaborator brings his expertise for a single component and simulation process. The framework does not require all the participants to use the same tool or the same modelling language. Experts are allowed to work independently in their own domains, using their own languages and tools (e.g., Nastran, LS-Dyna, Madymo, Abaqus, Ansys, Adams, Matlab, etc.). CAD solvers and internal codes can easily run on local resources, while CAE and CFD simulations may require a considerable amount of computational resources and software licenses, especially when running complex optimization or Design of Experiments (DOE). The models and processes they produce can be integrated into a broader system architecture model and executed in any computing node connected to the grid that supports all the chosen standards simultaneously or by use of a distributed execution framework that connects multiple, domain-specific computing nodes together into a live, concurrently executing computing grid.

Such a virtual collaboration can extend from integrators to suppliers to contractors. Models and Processes thus become the mechanism to collaborate and verify both function and progress at any stage of product development

SPDM: Simulation Process and Data Management

The SPDM system developed by ESTECO is a web-based enterprise application for the management of simulations. This system let users cooperate in the MDO use case and in several other use cases related to simulation workflow management. The concept of workspace and resources (see Figure 4) are the central concepts around which the whole system works. Four type of resources are defined in the SPDM system: users, computing resources, simulation workflows and simulation results (i.e. data generated by the execution of simulation workflows). Workspaces are isolated virtual spaces, used to group users, resources, simulation processes and data.

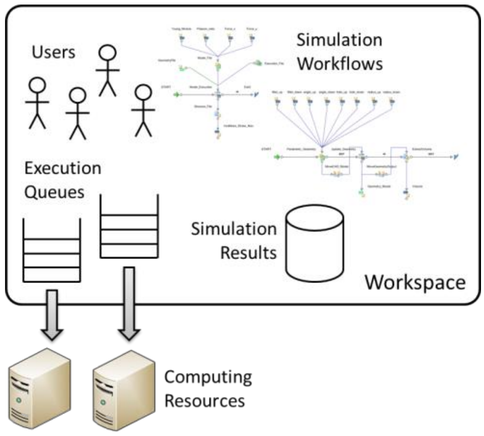

Figure 4. Workspace components

The SPDM system has a typical multi-tier architecture (Alonso et al. 2003) in which each tier provides a set of different functions. Specifically the following six tiers can be identified: logic, web, client, data, message, and business. Other components of the architecture are the system management and the high performance computing areas.

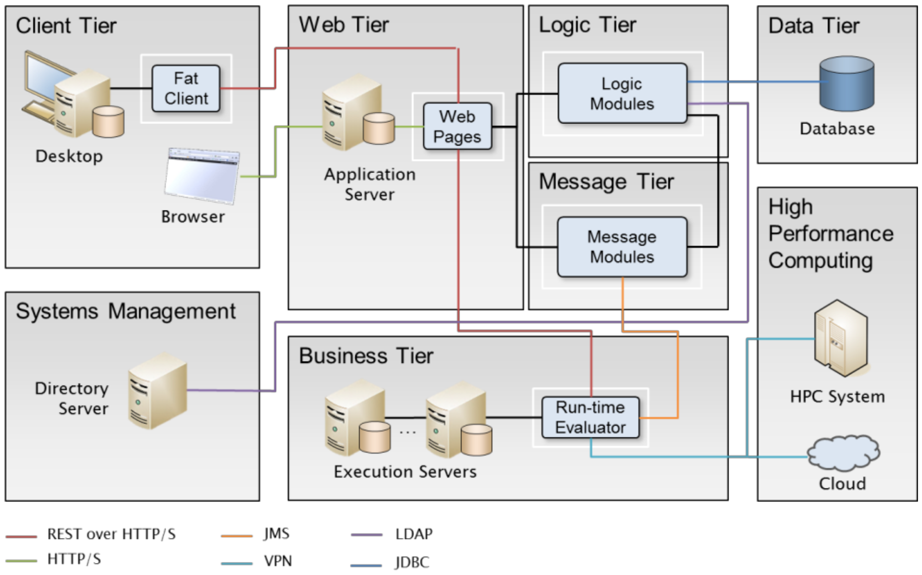

Figure 5. SPDM architectures and protocols used between tiers

Figure 5 shows the different tiers and components with their connections. The logic tier is responsible for: the execution of the application logic, the transfer of data with the data tier, and the integration with other enterprise applications (e.g. a directory server based on LDAP). The web tier produces results for the queries coming from the web, such results are in form of HTML pages and REST (Fielding 2000) responses. The client tier contains the client applications needed by users to interact with the system, a fat client for the creation of simulation workflows and a web browser to use the functions offered by the web interface are the possible clients. The data tier is responsible for the long term persistence of the data used by the application. While design data includes design requirements, objectives, constraints, and baseline designs, the design process data is mainly composed of the data produced when running the analysis. The message tier implements a queuing system and it provides reliable messaging functionalities to decouple the logic tier from the computing resources. Finally the business tier actually performs the execution of the simulation workflows on the execution servers or on dedicated computing resource for technical computing.

Real case study: Design and Optimization of a Wind Turbine power Unit

Such methodology has been tested on a real case regarding the assess and the optimization of the performances of a wind turbine power unit. Considering the turbine as the system, divided into three subsystems: the blades, the structure and the electric generator. At component level for the blade and the structure, there are the internal structure and the external shape. Considering the design of the blade and thus the calculation of the performances of the turbine, different models and levels of fidelity can be used to predict the aerodynamic performances and test the structural resistance. As an example the aerodynamic performances can be predicted through basic models, classical simplified numerical simulations, like blade element momentum theory based codes, or more complex CFD simulations. In order to achieve high energy productions, lower manufacturing and maintenance costs and at the same time deal with the complexity and the time of development, it is essential to optimize the design workflow as well.

The MDO Collaboration Process

In this study only the development of the blade has been taken into account without considering the structure or the electric generator. Only performances have been evaluated neglecting manufacturing costs. Tasks have been divided between three partners, each bringing their expertise in a specific field. Airworks is an engineering company and is in charge of the evaluation of the output performances. The Department of Engineering of the University of Trieste provided the expertise on the creation of a parametric CAD model and the knowledge on the CFD simulation tool. ESTECO had the tools, modeFRONTIER and SOMO, in order to perform the optimization study, create a full automated process linking together the different software and share the information, data and results.

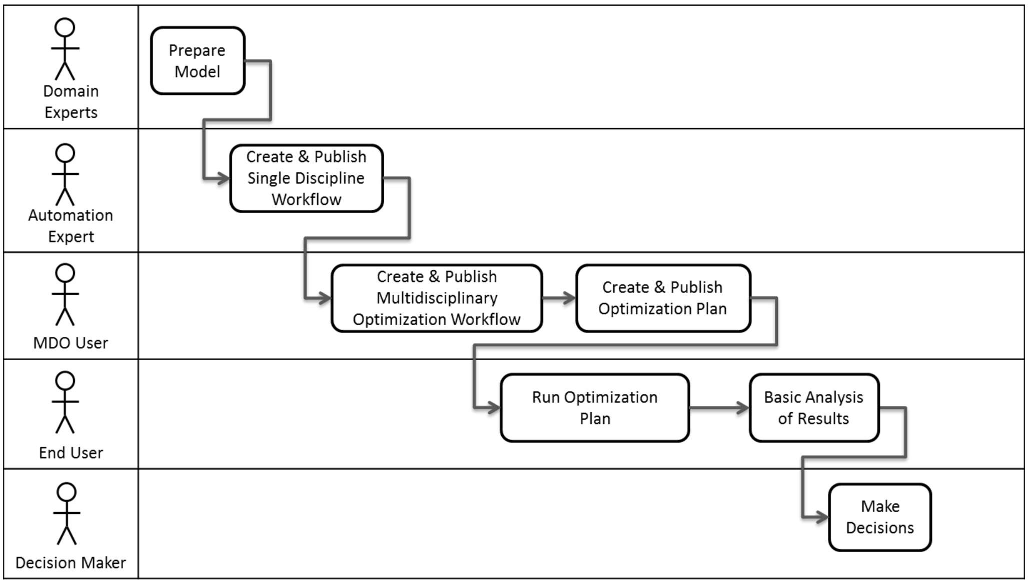

Figure 6. The MDO Collaboration Process

To simplify we can define roles in the design process:

- Airworks: end user, decision maker, blade structural expert
- Department of Engineering: CAD expert, CFD expert
- ESTECO: MDO user, optimization expert

The Domain Expert has knowledge in the discipline in which he is working (e.g. CAD, CFD, finance, electromagnetism, bio-informatics, etc.) and he is responsible for the preparation of the models that will be used by the applications involved in the simulation workflow. More domain experts are expected to take part in an MDO activity, and they have to make such models available to the next role taking part in the process. The Automation Expert has knowledge of the techniques and the languages used to define the simulation workflow. He is responsible for the definition and realization of the whole simulation workflow, he collects the models prepared by the domain experts and he defines and tests the simulation workflow, taking care of all the issues related to the integration of the different engineering applications and their interactions. The Automation Expert has also the responsibility to maintain the simulation process up to date with the last update of the models prepared by domain experts. Finally he has the responsibility to publish the simulation workflow making it available to the interested users.

The MDO User is an expert in optimization, he knows the optimization techniques and how to study the system under analysis in order to select the best optimization strategies. His knowledge covers also the techniques for design of experiment and system analysis. The MDO User is responsible for the creation of the multidisciplinary workflow, of the optimization plan, and for making the plan available to the other users. The definition of the optimization plan includes: definition of goals such as objectives and constraints, definition of the design space (e.g. decision variable bounds) and definition of the optimization strategies (i.e.

design of experiments and selection and configuration of the optimization algorithms). The next role in the process is the End User, such user is an engineer who uses the results of the simulations or optimizations to validate his assumptions or to examine different alternatives. He executes optimization plans, possibly varying some of the configurations of the original plan to explore different parts of the design space. Finally, the End Users prepare a report with the found solutions to submit to the decision maker. The last role involved in the MDO process is the Decision Maker, he collects the reports produced by the end user and select the best solutions found during the MDO process. The whole set of expertise and knowledge required to carry out an MDO activity are rarely found in one single engineer and usually it happens only for very small scale projects.

Because outside the scope of this paper, Figure 4 does not show the roles and the activities involved in setting up the environment for the execution of the MDO process.

Problem Description

The design of a wind turbine is a good example of multidisciplinary project. A possible way of dividing the whole design procedure is here summarized:

- The generation of a parametric model of the geometry and the CAD model of the blade
- The simplified analysis and optimization using a BEM code
- The local refinement and optimization in localized zones using a 3D CFD simulation
- The development and optimization of the electric generator and related components
- The structural design of the blades, the nacelle and the tower
- The aero-elastic analysis of the whole wind turbine

While the generation of the geometry and the BEM analysis are very fast, the CFD simulation requires both time and computational resources. On the other hand the number of configurations studied is very large in the first case compared with the full 3D CFD case.

Simulation Analysis Automation

Key feature required to improve simulation efficiency and exchange between players is the simulation process automation, enabled through modeFRONTIER workflow automation environment. It allows engineers to quickly define and build simulation analysis chains, defining both the logic and the data transfer.

The simulation are the controlled using parametric' interfaces. System parameters are split between inputs (green) and outputs (blue). Input parameters are applied to define the simulation analysis, output parameters are read as result of the analysis execution. modeFRONTIER allow to link multiple analysis tools from different domains.

The CAD geometry of the blades has been built considering a global parameter, which is the total length and the number of sections in which the blade is divided. Each section has a specific airfoil profile. Both twist and chord are not treated separately but there are two Bezier curves, which guarantee not to have steps between sections and have a smooth trend. This allows to limit the number of input geometrical variables to obtain a large number of different configurations and smooth profiles. The shape is determined by control points, which define a polygonal shape, in which the curve is bounded. The Bernstein polynomials explicit the de Casteljau algorithm, obtaining the following expressions for the x and y components of the points respectively:

(1) $$x(t) = \sum_{k=0}^{n} \frac{n!}{k!(n-k)!} t^k (1-t)^{n-k} x_k$$

(2) $$y(t) = \sum_{k=o}^{n} \frac{n!}{k!(n-k)!} t^k (1-t)^{n-k} y_k$$

In this work it has been chosen to use a second order Bezier curve resulting in four variable parameter, x and y coordinates of the two intermediate points, and four constant parameters, the spatial coordinates of the first and last point. This is a tradeoff between limiting the number of input variables and the possibility to create complex shapes and locally controlled patterns. Starting with a low number of parameters is not limiting because the technique of the degree elevation can used. This method, in fact, allows to increase the order of the Bezier function, performing a linear interpolation of the existing control points:

(3) $$P_{knew} = \frac{k}{n+1} P_{k-1} + \left(1 - \frac{k}{n+1}\right) P_k$$

This allows the reuse of the previous optimization results and the designs already evaluated do not need to be calculated again.

The complete 3D CAD geometry is built in an automated way coupling a CATIA macro with a Matlab routine which besides the input parameters previously described reads the airfoil shape points in the correspondent file stored in a shared library. During the creation of the library we understood that these was a limiting approach since aircraft airfoils had been developed for a completely different application. A new approach is to design custom built profiles for wind turbine characteristics. These could be cut back profiles or wings with flaps for example (Barlas & van Kuik 2007). The issue is then to calculate the performances in order to use them in analysis of the blade characteristics in the BEM code.

modeFRONTIER has also been used to reconstruct the lift and drag curve at different angles of attack. The chosen solution implies to perform a 2D CFD simulation using Star CCM+. The fluid domain is discretized using a polyhedral unstructured mesh. Near the surface prism cells have been used to correctly predict the gradient in the viscous sub-layer. Mathematically the equations have been resolved using the time averaged Navier Stokes equations (RANS), coupled with the Spalart-Allmaras turbulence model. At the airfoil surface wall no slip conditions have been used. In order to speed up the procedure it has been chosen not to modify the domain but to rotate the angle of the incoming wind direction. In this way it is not necessary to generate a different mesh every time, which for this type of calculation is a consistent part of the computational time.

In order to compute the performances of the turbine the WARP software developed and tested by Airworks has been used. This software can be divided into two fundamental parts: the calculation of the aerodynamic performances of the rotor through the BEM theory and the calculation of the output power curve and thus the electric production. This tool has been successfully coupled with modeFRONTIER and an example of the parametric workflow is shown below.

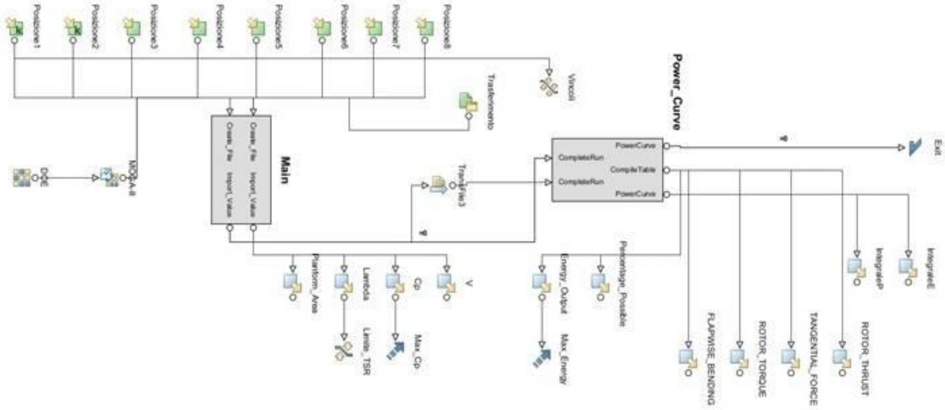

Figure 7. modeFRONTIER workflow integrating the WARP tool

The blade element momentum (BEM) theory is a simple and approximated analysis which, although, fairly reproduces the real performances of this kind of generator. The global aerodynamic performances of the blade are obtained dividing the blade in sections and summing the contribution of each considering no interactions or influence between these. The software extracts power output considering an annual wind distribution and a specific regulation for light and strong wind. A multi-objective optimization can be performed considering the power coefficient and the annual energy production.

Optimization Runs

Three different optimization runs have been performed. In the first only the aerodynamic profiles have been changed, in the second the chord and twist distribution while in the third all these parameters and the section division have been changed simultaneously. All results have been compared with the performances of a commercially available wind turbine developed by Airworks.

In the first optimization an issue regarding the airfoil type had be overcome. In fact, this is category variable and cannot be ordered in any way. Besides running a full factorial combination is not a feasible solution , since computational time would be too long. In order to optimize the configuration it has been decided to follow a particular sequence. Starting from a baseline configuration a section at a time has been changed starting from the tip and moving to the root. This iteration has been done for every section giving at the end a enhance in power coefficient and annual energy production of 1.26% and 0.47% respectively.

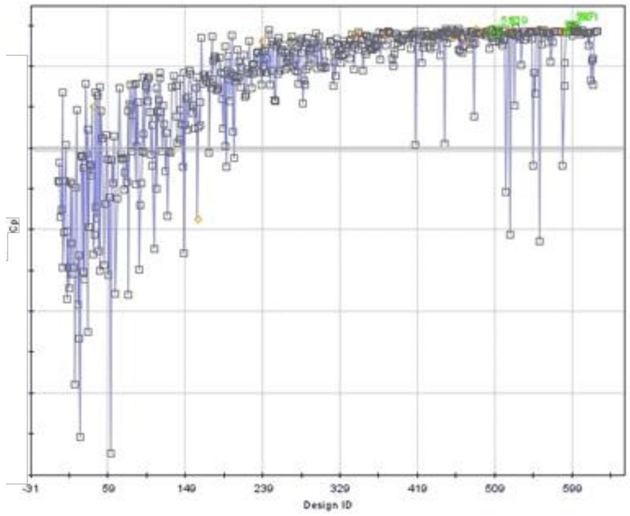

Figure 8. The convergenceof the value of Cp using the genetic algorithm

The second optimization regards chord and twist distribution. The starting trend has been obtained for both using the Schmidtz formulas and then, using the Bezier curves, these have been changed during the optimization as can be seen in the figure.

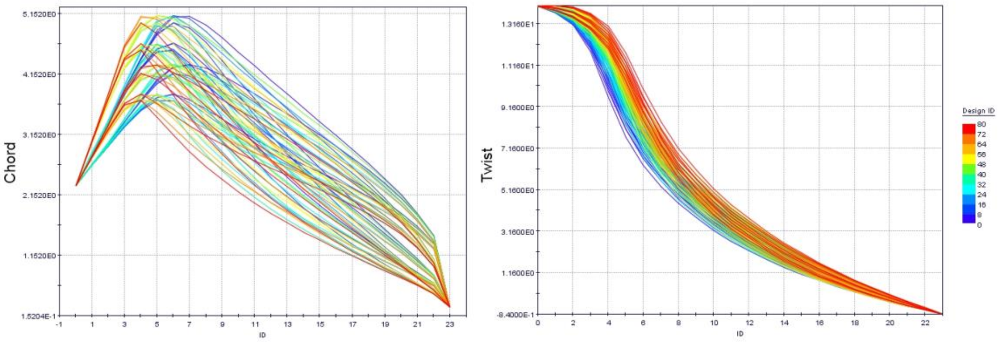

Figure 9. The evolution of chord and twist distribution during the run

The third optimization all these parameters have been considered at the same time for a total number of 24 input variables. A MOGA II genetic algorithm has been chosen considering a population of 19 designs, taken from the previous runs, and 53 generations. This lead to a total number of 1007 evaluations. Results of the previous optimizations have been enhanced further leading to an increase of 1.84% in the power coefficient and 2.28% of annual energy production.

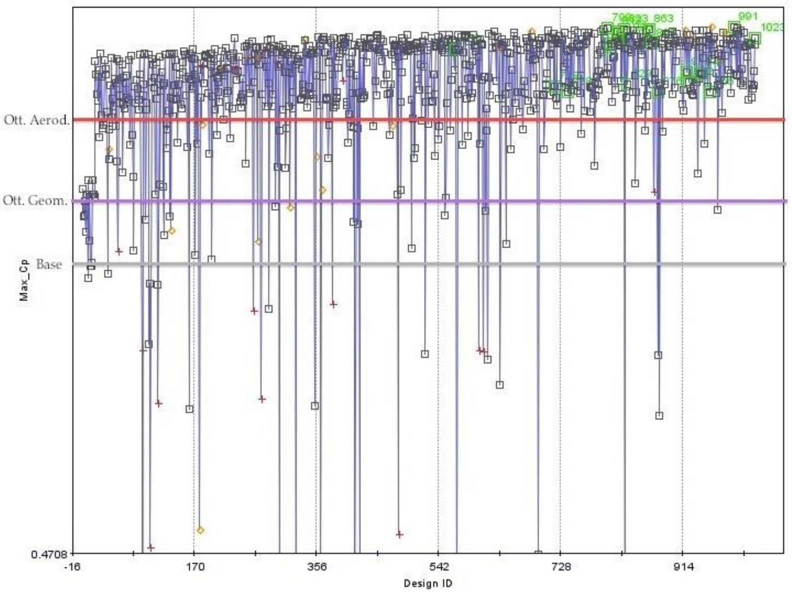

Figure 10. Results of the last optimization run for the power coefficient

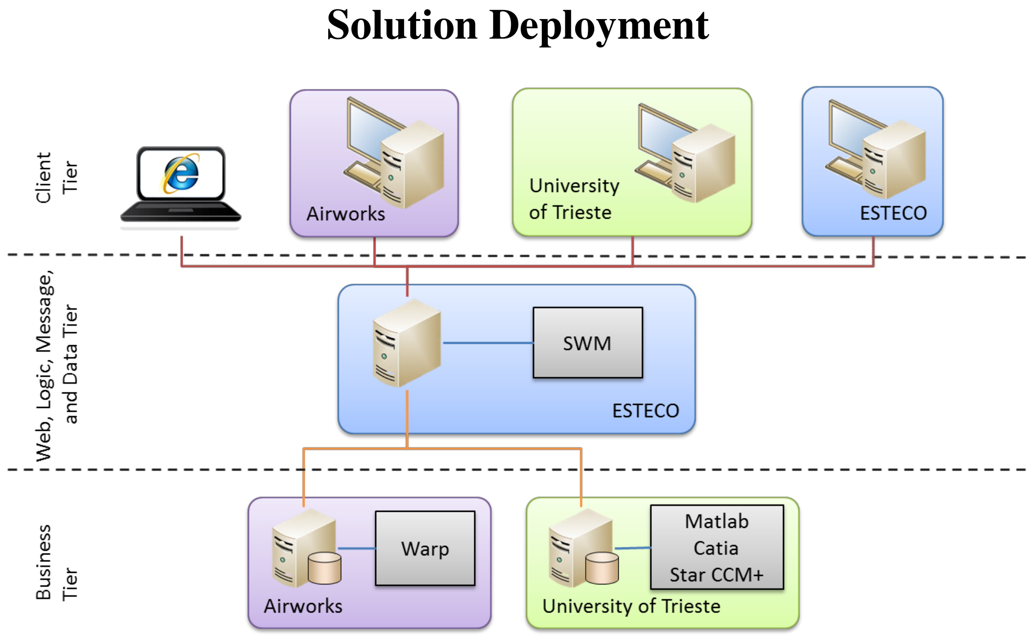

Figure 11. Implemented deployment.

Figure 11: shows how the whole system has been deployed. In the client tier there are the web browsers used to interact with the system and the fat clients used to create and publish the simulation workflows, both the single discipline and multidisciplinary ones. The SPDM system, SOMO, hosted by ESTECO contains four tiers: web, logic, data and message. It has been made available in Internet through secure communication protocols such as HTTPS. The business tier has been deployed over different organization providing the needed computing resources. Airworks provided

the necessary resources to run the WARP legacy code, the University of Trieste provided the computing resources to run Matlab, Catia and Star CCM+.

Conclusions

The system engineering approach, together with the capabilities of the ESTECO products, have been successfully used to build and manage a simulation workflow for the design and optimization of a wind turbine. The correct definition of roles, determined by specific competencies, the standardization of simulation processes and the use of a shared repository have enabled the collaboration between different domains experts sharing and managing multiple design analysis together with the capability to run optimization (trade-off studies) and have determined to reach the goal of enhancing the performances of the wind turbine.

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Biography

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Current position / tasks

After an experience at Airbus Flight Physics Methods and Tools, Matteo joined ESTECO where he is now the Enterprise Solutions Product Manager. In this role is in charge of client engagement management, requirements gathering and roadmap building. Responsible for analysing market conditions and defining features or functions of ESTECO products.