A Collaborative Engineering Platform for Supporting Design Optimisation of Advanced Aero Engine Sub-Systems

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Abstract: Modern engineering design optimisation processes require an increasing distribution of calculation activities between distributed collaborating teams, laboratories, Universities and companies. The aerospace industry has an increasing need to establish efficient Collaborative Frameworks between partners with the aim at reducing design redundancies and accelerating the required design optimisation loops, moving the focus from separated centres towards a strongly connected innovation network. This paper will present an Italian collaborative innovation network involving Avio S.p.a. and his two university research centres Great Lab and ePaintLab. The scenario presented is focused on the collaborative network set-up aiming at addressing advanced multi-disciplinary design optimisation strategies supporting next generation of jet engine sub-systems design.

Keywords: Collaborative Engineering, Extended Enterprise, Multidisciplinary Design Optimisation, Collaborative Optimisation

1. Introduction

Collaborative Engineering (CE) is about the development of processes in its organization, management, and methodology, integrated with innovative development technologies. With the trend towards global competition and the rapid advances of the Internet technologies, nowadays, extensive research and development have been made supporting distributed applications to form a wider landscape, in which geographically dispersed users, systems, resources and services can be synthesised across enterprises in an Internet/Intranet environment beyond the traditional boundaries of physical and time zones. Face-to-face communication and cooperation is impossible in this situation. Some traditional communication methods that are used in a traditional CE environment, such as emails, discussion forums and net-meetings, are not fully satisfactory. To address this issue, Internet-enabled Collaborative Engineering and the related techniques are developing at a rapid pace since the end of the last century.

An Internet-based collaborative design environment consists of two capabilities, namely, distribution and collaboration. Distribution means systems that are geographically dispersed can be linked to support remote design and optimisation activities, while collaboration allows individual designers to be associated and coordinated to fulfil a global design target and objective. A collaboration mechanism requires the specific design of a distributed architecture of a system to meet the functional and performance requirements. An Integrated and Collaborative Environment (ICE) for product development is actively being investigated to incorporate the two strategies to meet the following requirements:

1. **Enterprise integration for the distributed organisations and systems**. Manufacturing companies and research centres can be integrated with their distributed systems and partners, such as customers and suppliers, via networks to establish an ICE for product development.
2. **Heterogeneous environments and interoperability of software tools.** An ICE will allow the integration and interoperability of heterogeneous software and hardware. Information environments and legacy systems in companies are usually based on different programming languages, representation languages and models for product information, and computing platforms. To achieve an effective and efficient interoperation and interaction of sub-systems and software components in such heterogeneous environments, automatic information conversion and interpretation capabilities are necessary to realise obstacle-free information communication and workflow control.
3. **Open and scalable computing structure and services.** There is a need to provide a possibility to dynamically integrate new sub-systems into or remove existing sub-systems from an ICE-enabled product development with high convenience, security, reliability and without stopping and re-initialising the entire environment. New kinds of service architectures to wrap software tools have to be developed to incorporate them into the environment as required, so as not to interrupt organisational links previously established.
4. **Cooperation between humans, and between systems and humans.** People and software systems need to work at various levels of collaboration, and with rapid access to knowledge and information repositories. Bi-directional communication infrastructures are necessary to allow effective and quick communication between systems or between humans and systems to facilitate their interactions.

This paper will focus on a design and optimisation platform for next generation jet engine sub-systems, as advanced power gearboxes, low emission combustion systems and high efficiency low pressure turbines, within a distribute and federated product development framework. Particular emphasis is placed on reporting the experience on solving complex distributed problems through the use of decomposition strategies.
The results presented in this paper raise from the collaboration between Avio S.p.a., a large Italian aerospace company leader in aerospace propulsion, and his university research centres: Great Lab, situated in the *Politecnico di Torino* Campus, and ePaintLab at *Università del Salento*.

Great Lab (Green Engine for Air Transport Laboratory) is the first Italian research centre for the development of strategic technologies for producing environment-friendly aircraft engine sub-systems. The partnership agreement signed in April 2008 between Avio S.p.a. and *Politecnico di Torino* has led the constitution of this integrated University-Enterprise innovation centre situated in the *Politecnico di Torino* Campus. Great Lab is an integrated multidisciplinary laboratory that hosts a research group consisting of 7 researchers and 14 researchers assistants of *Politecnico di Torino* and it articulates in seven technology areas.

Great Lab is providing major advance in developing the next generation commercial aircraft engine technologies, enabling to investigate high–performance, low noise and low emission engines sub-systems and components.

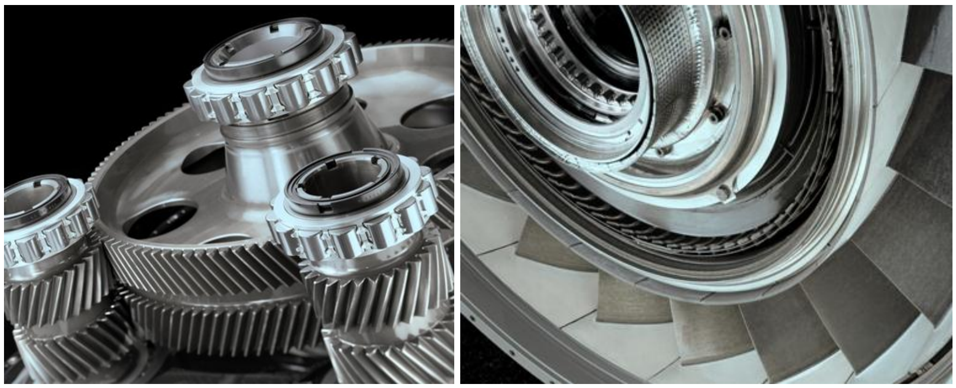

Figure 1: Avio is a world-wide leader in the aerospace industry and has one of the richest histories in the realm of science and technology of flight.

The purpose of Great Lab is to coordinate joint research activities, to individuate topics of interest for the growth of the Aerospace District in Piedmont, to monitor the international scientific panorama for the individualization of innovation ideas, to create a sector of integrated expertise and human resources, also with the aim to rationalize the joint resources. This partnership creates a cross-cultural working environment for Avio and *Politecnico di Torino* staff in areas of basic science, applied research, staff training, and technology transfer, where *Politecnico di Torino* can benefit from privileged access to Avio capability bases and information networks.

Figure 2: Great Lab, Avio and Politecnico di Torino integrated research centre.

ePaintLab derives its name from "Avio-ISUFI Partnership for New Technologies", to which was added the universally recognized symbol of new technology, "e" (such as e-business, e-learning ...). The collaboration between Avio and the Università del Salento, was launched in 2003, when a few researchers, experts in the topics of knowledge management and collaborative work environments, settled in Turin at the headquarters of Avio, to gain confidence on issues related to new product development. The ambition of ePaintLab was to consolidate, in partnership with the *Università del Salento*, a centre of excellence and innovation for new methodologies and technologies to support New Product Development processes. The laboratory is planted at the *Università del Salento* and works through joint research programs ranging from regional to national and even international projects.

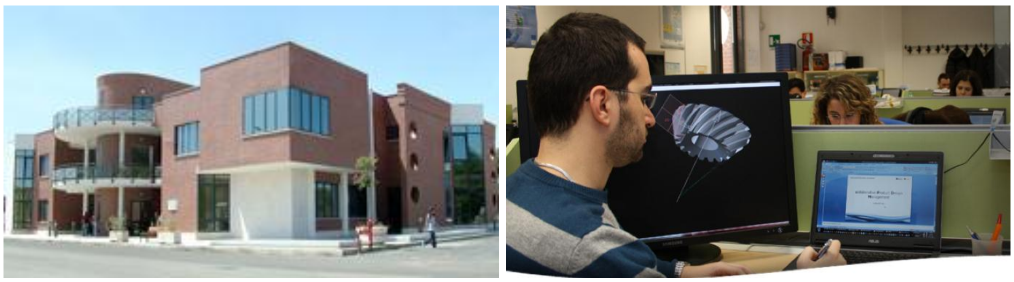

Figure 3: The Euro-Mediterranean Incubator in "e-Business Management" that hosts the ePaintLab in Lecce

After a first period of experimentation, the collaboration between Avio, Great Lab and ePaintLab is a real example for companies and research centres on how to greatly enhance technological assets, share know-how enabling efficient paradigm in design and optimisation methodology.

2. Enabling Collaborative Engineering

Collaboration Engineering is an approach to the design of re-usable collaboration processes and technologies based on two main characteristics: distribution and collaboration. In order to develop these capabilities and to obtain an effective implementation of the multidisciplinary approach within engineering tasks, a suitable hardware and software infrastructure is needed. For this reason, with the aim of spread calculation activities related to this research work, through a multi-site point of view, an Internet distributed approach was developed. The network connects three main research centres, geographically distributed in three Italian sites, Torino, Rivalta di Torino and Lecce. In Figure 4 a sample optimisation process, used as test case to validate the Collaborative Engineering platform, is shown.

The infrastructure needed to carry out federated processes has been obtained thanks the Isight/Fiper technology, a P.I.D.O. (Process Integration and Design Optimisation) solution, able to represent the Collaborative Engineering and the Design Automation philosophies. Thanks to this solution, several calculation tools were integrated in order to define a multidisciplinary optimisation process geographically distributed. Here below some details of the implemented architecture and its main features.

Isight is the process manager used by engineers to design simulation processes. Calculation tools, both commercials and in-house developed, are integrated inside Isight with the aim of automating the design search investigation and identifying the optimal solution. Isight gives the user the chance to implement several tolls to investigate the design space, like Design of

Experiment (DoE), surrogate models, Design for Six Sigma (DFSS), Monte Carlo Simulation (MCS), Single-objective and Multi-objective Optimisation techniques. Thanks to Isight the user can specify where each component of the workflow will be executed, setting the so-called "affinities".

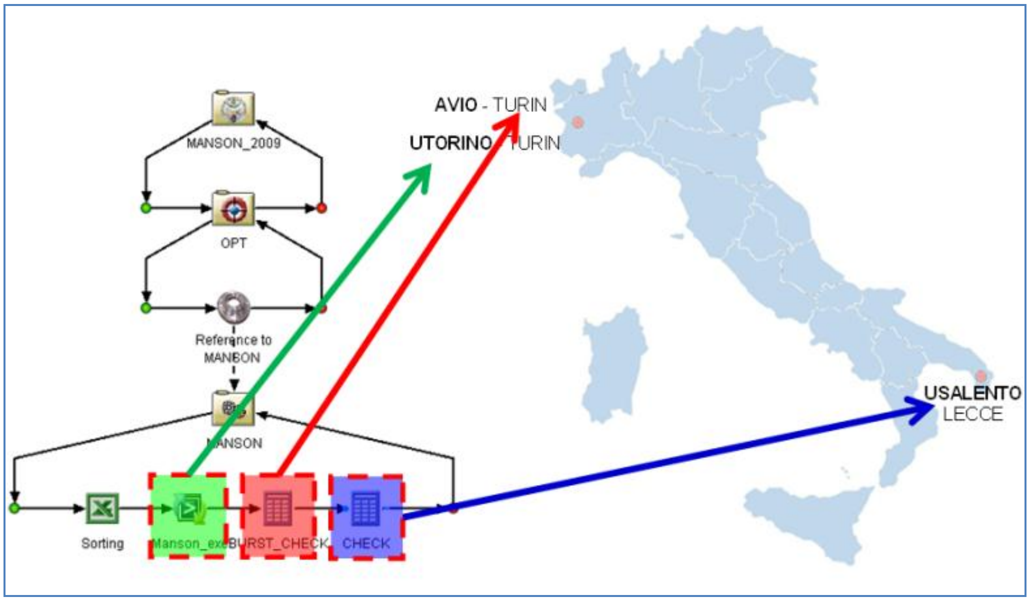

Figure 4: Collaborative Framework

The server element is called FiperACS and it is the engine that orchestrates the execution of analysis processes spreading them on hardware and software resources even geographically distributed. Based on IBM Websphere™ Web Application Server, it hosts the processes published by users and manages the distribution of jobs on those workstations equipped with a FiperStation. FiperStations are the those elements of the architecture installed on workstations or computational clusters (achievable by the FiperACS server) that are delegated to execute the whole workflow or some calculation activities. Setting-up a specific property of each FiperStation, named "affinity", users can define where to spread the calculation activities making clear the availability of a specific software (eg Nastran solver) able to carry out a particular type of job. Each network unit can participate to the execution of a process through the use of FiperStations.

On IBM Websphere™ Web Application Server was loaded, also, the web interface so-called Webtop. Calculation processes published in the Fiper framework can be visualized and executed even through the web interface. By Webtop all authorized user can specify the parameters for each process and start an optimisation job. Thanks to this interface, the FiperACS execution engine can show the results both numerically and through various types of graphs of trends.

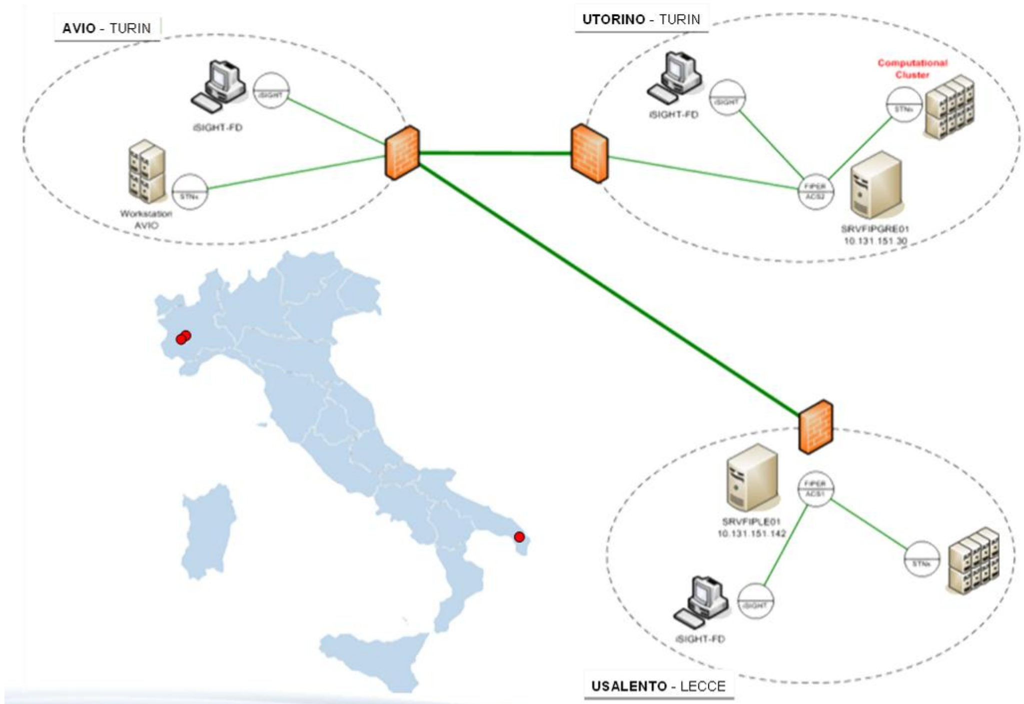

Figure 5 : Collaborative Infrastructure main actors

The software main elements described above were used to create the Federation and distributed computing architecture between Avio, Great Lab and ePaintLab located respectively in Rivalta di Torino (Turin), Turin and Lecce, according to the diagram shown in the Figure 5.

The infrastructure presented was used to carry out different Multidisciplinary Optimisation test cases oriented to the investigation of next generation aero engine sub-systems.

3. Network Details

ePaintLab has adopted a network infrastructure which connects the laboratory directly to an high speed optical fiber IP/MPLS backbone. This infrastructure reserve to the ePaintLab a private network inside the network of a national provider of connectivity on which it was possible to realize a MPLS channel between ePaintLab and AVIO through a VPN (Virtual Private Network) site-to-site with a guaranteed minimum bidirectional bandwidth of 60Mbps. The connection provides L4 reliability (Fast Time Recovery equal to 4 hours in 95% of cases, 8 hours in 100% of cases) and availability for 99.5% of the time due to physical redundancy of equipments and routes. All this is achieved by using a pair of CISCO router 720x at the site of Lecce and two CISCO routers 380x at Avio in Rivalta of Turin, providing a low latency connection (25ms rountrip) with redundant paths and devices on a direct connection to MPLS backbone via dual redundant circuits on optical fiber. The perimeter of such interconnection has been extended until the seat of *Great*

Lab hosted in the Politecnico di Torino enabling the interconnection between all the three research centres.

4. Deal with multidisciplinary problems

A discipline can be identified with a particular branch of engineering. For example, some of the disciplines involved in the design of an aero-engine are aerodynamics, thermodynamics, stress analysis, thermal analysis, etc. In this view, a single discipline is concerned with all the physical components of the final design. However, this division is often difficult to implement, in that generally not all the aspects are analysed by a single disciplinary team, but rather are responsibilities of different project partners. Therefore, for practical reasons it pays to consider a discipline more as an element of the project partnership (company, team) than a theoretical field.

Fundamentally, there are two ways to deal with multi-disciplinary problems: either by an integrated model or by a decomposed one.

A system like an aero engine is a complex assembly of a large number of different components. For this reason, the most realistic manner to model the problem is to connect together the mathematical models of the sub-assemblies, accurately modelling the interaction. Hopefully, this should result in a model capable of reproducing the whole range of behaviors of the system, or at least the significant ones. Such a possibility is of paramount importance in the design of complex systems, especially in the preliminary phase

5. Classification of the decomposition methods

What follows is a rough classification of the methods for the problem decomposition, which can be found in *literature*.

Hierarchical methods. The decomposition generates a rigid map of relations between the constituent elements. No element can be moved without destroying the dynamics of the whole designed product.

Non-hierarchical methods. The elements of the decomposition are all equally important, namely there is no fixed order of distribution.

The ***Analytical Target Cascading*** (ATC, (Kokkolaras, Mourelatos, Papalambros, 2004)) belongs to the first class. The ATC is mainly used in the Automotive field, and its peculiarity is that it mimics the production process of the car. No equivalent of the ATC seems to exist in the Aerospace Industry. Due to this and to the rigidity of its structure, the ATC will not be considered in the following.

The second class embraces many methods, and it corresponds to the ***Multidisciplinary Design Optimisation*** (MDO, (Giesing and Barthelemy, 1998), (Kodiyalam and Sobieszczanski-Sobieski, 2001)) methodology in the strict sense of the definition. Non-hierarchical methods can be divided into two sub-classes, namely:

One-level methods. All the blocks are at the same level of importance, and their coordination is left to the blocks themselves. In this class there are the ***All-in-One*** (AiO), the ***Distributed Analysis Optimisation*** (DAO) and the ***Simultaneous ANalysis and Design*** (SAND) (Cramer, Dennis, Frank, Lewis, Shubin, 1994).

Two-level methods. All the blocks share the same level of importance, but their coordination is the task of an additional block. To this class belong the ***Concurrent Subspace Optimisation*** (CSSO, (Lokanathan, Brockman, Renaud, 1996)), the ***Collaborative Optimisation*** (CO), the ***Bi-Level Integrated System Synthesis*** (BLISS, (Sobieszczanski-Sobieski, Agte, Sandusky Jr., 1998)) and the ***Inexact Penalty Decomposition*** (IPD, (DeMiguel, Murray, 2006)).

The approaches contained in the class of the two-level methods have found some applications in the design of aeroengines sub-systems within the Collaborative Framework involving Great Lab and ePaintLab.

Within a multidisciplinary problem, the following three categories of variables can be identified:

Local variables. Are those variables which pertain to a single discipline.

Global variables. Are those other variables which are shared by more than one discipline.

Coupling variables. These are those disciplinary outputs, which enter some other disciplines as input variables. Logically, the discipline which receives the information must wait for the first one to generate it. This is what would be necessarily done within an integrated model; however, in a decomposed problem this difficulty is solved by means of targets.

For any decomposition method of this class, the decomposed formulation of a problem will be as much equivalent to the original one as there are few connections between the (Alexandrov, Lewis. 2000).

6. A Decomposition strategy: the Collaborative Optimisation (CO)

The Collaborative Optimisation (CO) is probably the most popular non-hierarchical, bi-level approach existing in literature. Its original formulation was given in (Braun, 1996), with further developments in (Braun, Kroo, 1997a), (Braun, Kroo, 1997b), (Kroo, 1996), (Sobieski, Kroo, 1997).

The manner in which the CO breaks these links looks very much like the strategy used for the analysis of hyperstatic structures, or of any other underdetermined system. Using the example of structural analysis, the logical steps performed are the following three:

1. A number of degrees of freedom are artificially created within the structure by breaking some internal links. As a consequence, the structure is "statically determined", namely the global state can be assessed through the equations of the static equilibrium.
2. Together with the novel degrees of freedom, an equal number of unknowns are introduced. These correspond to the forces which the breaking of the links has undone. Therefore, the system of equations written at point 1 contains more unknowns than equations, and other equations must be added.
3. The additional equations are the congruence equations, namely equilibria of forces generated internally by considering the elasticity of the materials. This restores the lost congruence and allows for the univocal determination of the state of the structure.

Similarly, in the CO the sub-problems links are broken, and a number of auxiliary variables is created within each sub-problem, indicated by the symbol σ, which mirror the global and coupling variables. The auxiliary variables are unknowns, and correspond to the forces originated by the broken links, as said at point 1. In the CO structure, the auxiliary variables are optimisation variables, which are added to the existing local variables.

Above the set of sub-problems, an additional task is built in order to control step-by-step the whole activity. Specifically, what this task is required to do is:

- to coordinate the sub-problems' efforts towards the satisfaction of the design requirements;
- to provide the additional equations, corresponding to the congruence of point 3;
- to satisfy the global constraints.

At the same time, a generic sub-problem must:

- participate to the restoration of the lost links;
- pursue local objectives;
- satisfy local constraints.

In the CO approach, the original problem is decomposed into 2 disciplines; $\sigma 1$ and $\sigma 2$ are the auxiliary variables defined in sub-problems 1 and 2, respectively; they mirror the global variable s. In the system problem the coupling variables a1 and a2, are substituted by target variables, t1 and t2, which become variables of the system problem. The f in the system problem is the set of global objectives. Operatively, the optimisation of a CO decomposition proceeds as follows :

- the sub-problems perform their optimisations completely on their own account, with no reciprocal communication (in parallel), and transmit the results to the system problem;
- the system problem performs one step of its optimisation, updating targets and global variables;
- the new targets and global variables are passed back to the sub-problem;
- all this continues until some convergence condition is satisfied.

7. Advantages and Disadvantages of the Collaborative Optimisation

During the research activities carried out at Great Lab and ePaintLab, with the use of the Collaborative Platform described in this paper, a set of advantages and disadvantages offered by tha CO approach has been detected:

Independency of the sub-problems. Contrarily to other strategies of decomposition, in the CO the single sub-problem is thoroughly independent. Its only contacts with the other sub-problems pass through the target and global variables. Thanks to the independency, within a sub-problem it is possible to work with the methods and tools usual to that task. A practical consequence of this is that there is no need to change anything in a sub-problem in order to set the collaborative environment. No novel methodology to learn or new software to use. Every company or disciplinary team can take its own project decisions in a completely independent manner. It just has to meet the targets it receives from the system problem.

Parallelization of calculus. The CO lends itself very naturally to the parallelization of the calculus. Thanks to this, the distributed hardware resources can be exploited.

Alongside with these advantages, the following drawbacks are identified:

Increased size of the problem. The number of variables of the problem is increased by the introduction of the auxiliary variables.

Inefficiency of the existing algorithms. System problems and sub-problems are generally solved by means of the most common optimisation algorithms. Unfortunately, these algorithms were created for classical MP, and hardly fit for decomposed structures.

Breakdown of the KKT optimality conditions. Beside the inefficiency due to the nature of the algorithms, within the CO it must be noted that the well-known Karush-Kuhn-Tucker (KKT) optimality conditions fail when the search reaches an optimum. This is an important point, in that the KKT conditions are used as a stop criterion. Much has been written in literature about this topic; a good explanation of it can be found in (Alexandrov, Lewis. 2000). The practical aspect of this is that when the optimisation reaches an optimum, then the KKT failure destabilizes the convergence. Therefore, the search point in the design space suddenly “jumps” away, and the exploration restarts from that point.

A trivial manner to avoid the breakdown of the KKT conditions consists in using a non-gradient-based algorithm for the solution of the system problem. Such an algorithm is, for example, a Genetic Algorithm. However, this would involve an unacceptable amount of computational time, and therefore is unviable in practice, unless surrogate models are considered instead of analytical ones. Another manner to sidestep the problem is to loosen a little the conditions for the congruence of the sub-problems, written as constraints of the system problem. In so doing the system problem is a little “relaxed”, and thus it is supposed to approach an optimum without going exactly into it, which would make the KKT conditions break. However, this second method is discouraged in that the relaxation could be too big, and therefore the solutions found could not be implemented in practice due to a lack of congruence. From the same experiments, the partners reached the conclusion that the best approach to the use of a CO consists:

- Using gradient-based methods at the system level;
- Constantly monitor the time-history of the parameters, in order to identify the moment when these jump away from a horizontal asymptote, corresponding to the KKT failure: the iSight software could help in monitoring, both in standalone processes and in distributed ones, providing useful tables and graphs tools for monitoring parameters time history and providing the value of the optimum or the Pareto frontier;
- Possibly, stop manually the search when the above happens, even if large scale and spread MDO projects usually should not require the user to attend at the optimisation runs.

A solution must be found within the set of points which have performances close to the assigned requirements, or which at least represent an improvement with respect to the starting point. The solution(s) must be congruent, namely the couplings between disciplines must be good.

8. Conclusions

Frequently, large design project require the collaboration of several distributed teams, which combine their specific skills and tools in order to pursue a common goal. In this manner the partners share risks and rewards of their activity, and adapt their own business and experience. This document addressed some practical problems occurring within a collaborative design environment.

Over the last few years the robustness of the design procedure has gained more and more importance, in the presence of fierce competition which industrial companies must face. Recently, concepts such as right-the-first-time, virtual enterprise and collaborative business had been developing, becoming cornerstones of modern industry. This paper is related to an Italian collaborative innovation network, involving Avio S.p.a and its university research centres: Great Lab, situated in the Politecnico di Torino Campus, and ePaintLab at Università del Salento. The presented scenario is focused on the collaborative network set-up aiming at addressing Collaborative Optimisation strategies for next generation of aero engine sub-systems.

The infrastructure needed to carry out federated processes has been obtained thanks Isight/Fiper and the Design Automation philosophies. Thanks to these solutions, several calculation tools were integrated in order to define a multidisciplinary optimisation process geographically distributed. The next step is focused on the improvement of the process, also including other CAx tools to allow researchers to transparently use a design “tool box” without caring about the physical location of the single tools. For this reason the collaborative platform will be enlarged including collaborative tools, like CMS (Content Management System) and web conferencing services where users could share desktops, show slides, collaborate, chat, talk and broadcast via webcam.

On the side of optimisation, the Multidisciplinary Design Optimisation provides a range of techniques for dealing with non-integrated designs. Integration is impossible in the case of a project developed in partnership or in other similar cases. These techniques are known with the name of decomposition methods. All the decompositions belonging to the MDO are non-hierarchical, namely the blocks of the decomposition have all the same level of importance. In other words, these blocks are not linked together by a rigid structure, which would impose a univocal direction to the flow of operations. Rather, the blocks can be scattered, added or removed in and from the operational structure. Some literature indicates the Collaborative Optimisation (CO) as the decomposition method of choice for the design of aero engines. The actions to perform in the CO are, essentially: (i) to define the boundaries of the separate blocks, called sub-problems; (ii) to set up an superstructure for the management of the overall activity, called system problem; (iii) to define the connections between sub-problems and system problem. The sub-problems are made independent of each other.

Likewise an orchestra director, the system problem will drive the course of the whole activity towards the satisfaction of the project requirements. This will be done by means of an optimisation procedure. Beside the advantages, the CO is characterized also by some drawbacks. One of these is the mathematical difficulty deriving from the use of optimisation algorithms, which were devised for ordinary, integrated problems.

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