Challenges to overcome for routine usage of automatic optimisation in the propulsion industry

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ABSTRACT

In industry, there is an ever-increasing requirement not only to design high performance new products but also to deliver them at lower cost and in shorter time. To meet these demanding engineering challenges, it is not sufficient to treat the different disciplines involved in a product design in isolation; rather they must be considered together as an integrated system that reflects the dependencies and interactions of the different disciplines. The design process must be automated to meet the stringent design time-lines. In spite of promising forays for over a decade, automatic design optimisation (ADO) and multidisciplinary optimisation (MDO) has not been widely adapted by the Turbomachinery design practitioners. This presentation will explore some of the technical and non-technical barriers such as cultural and organisational issues that must be addressed if ADO/MDO is to be used routinely in industry. Some recent, successful application of automatic optimisation is also reported herein.

NOMENCLATURE

ADO	automatic design optimisation
API	application program interface
CGNS	CFD general notation system
COTS	commercial-off-the-shelf
CPU	central processing unit
FFD	free-form deformation
GA	genetic algorithm
GPU	graphics processing unit (a single chip processor)
GUI	graphical user interface
LE/TE	leading-edge — trailing-edge (of a blade)
LSF	load sharing facility
HHB	Hecks-Henne bump function
HPC	high performance computing (e.g. clusters of PC)
MAM	mid-range approximation method
MDO	multi-disciplinary optimisation
NURBS	non-uniform-rational-B-splines
OGV	outlet guide vane
OS	operating system (of a computer, e.g. Windows, Linux,…)
PCA	principal components analysis
PDE	partial differential equations (e.g. elliptic, hyperbolic, ...)
POD	proper orthogonal decomposition
SGE	sun grid engine
STEP	standard template for electronic publishing (ISO 103033-21)
n	number of design parameters
scp	remote secure copy
ssh	remote secure shell

1.0 INTRODUCTION

Tools with different TRL (technology readiness level)[1] are used at different stages of design. However, it is well known that 80% of cost-performance of a product is locked into a design in the preliminary stages. Hence, it makes sense to use tools with higher TRL

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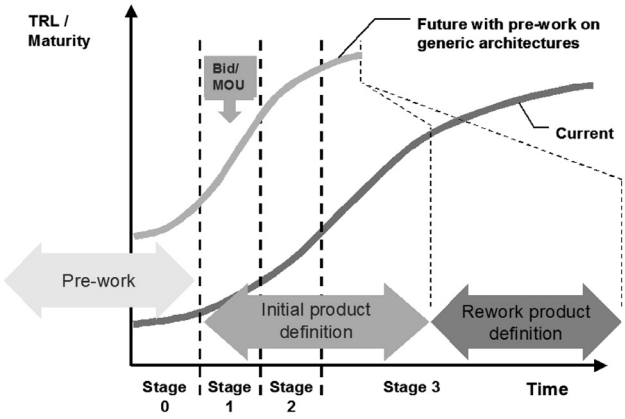


Figure 1. Evolution of design from conceptual, preliminary stages to detailed design versus technology readiness level.

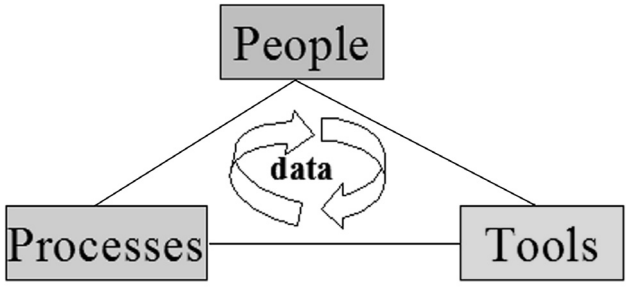


Figure 2. Three pillars of the design.

level 4-6 even at the conceptual stage where fast, automated design tools are needed. Figure 1 depicts the evolution of a design from conceptual design to detailed design. It is recognised some 'pre-work' is needed to produce a fully automated, mixed fidelity MDO capability right at the beginning of a design where customer requirements are inputted as objective functions and constraints; multiple solutions are then generated to allow rapid trade-off studies to be carried out. The preliminary design, at Stage 1, is multi-disciplinary in nature where interactions of components need to be taken into account. Using higher TRL level design techniques at the beginning of a design cycle is quite challenging requiring to over-come a number of technical and non-technical barriers, which are discussed in this paper.

Three main pillars of the design process are shown in Fig. 2. People, processes and tools are at the core of organisation's engagement in any engineering design, the data layer is where the flow of information occurs. The ability to capture, curate, access, process, manipulate, and understand a large amount of data are some of the key challenges facing the industrial engineering community. Hence, attention should not solely be focused on improving the tools or even processes without paying attention to the people's need, training, and support.

Aerothermal design of turbomachinery components and systems is a complex task which needs to satisfy an increasingly diverse set of design requirements, e.g. split of work, reaction, mass flow, aerodynamic loss, maximum stress, fatigue loads, weight of components, and aero-acoustic levels, etc. Meeting these stringent requirements simultaneously often leads to near equality constraints, which necessitates the use of advanced optimisation techniques[2].

Progressively, high fidelity simulation is used to model the problem under the study and design which leads to massive HPC (high performance computing) requirements. Examples of such high-fidelity simulations are shown in Figs 3 and 4. Although,

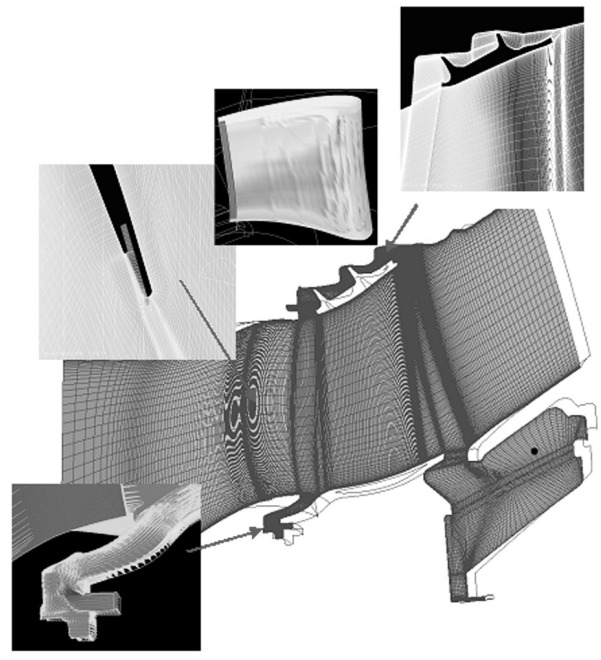


Figure 3. High-fidelity representation of a HP turbine stage, including the bleed cavities, shroud, TE and surface cooling[3].

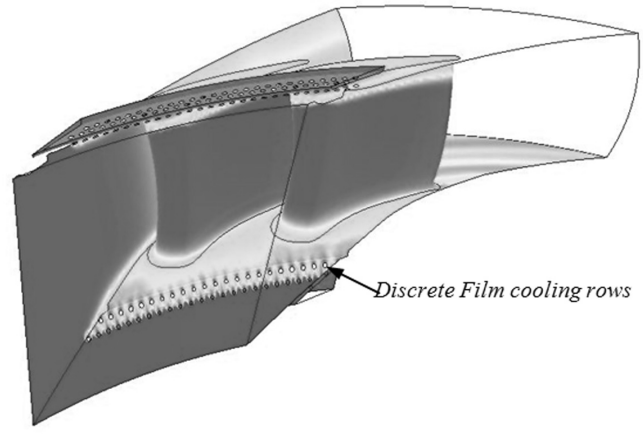


Figure 4. Adiabatic wall temperature contours — high-fidelity platform film cooling simulation.

industry recognises the need for investment in HPC facilities, the resources are shared with many other users who traditionally have been using an infrastructure and queuing system designed for 'design by analysis' approach. This is not suitable for an automatic optimisation approach.

1.1 Technical issues

It is the author's firm belief that seven steps need to be executed effectively before an automatic optimisation can successfully be carried out. These are as follows,

- Parametric geometry constructions and/or shape morphing capability
- Automatic, rapid and robust mesh generation
- Robust and accurate simulation solver (CFD, FE, cost modeller, ...)
- Post-processing and simulation (CFD, FE, …) data extraction

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- Advanced optimisation algorithms, including design space visualisation and data-mining, screening, ranking, surrogate modelling, efficient and robust constraint handling
- Work-flow and data management — including exchange (and often interpolation) of data between different disciplines need to be standardised and made automatic
- Computing resources and other IT issues
  - HPC power, i.e. number of cores available
  - Queuing and scheduling software (e.g. LSF, SGE) suitable for optimisation, i.e. HPC resource that recognises optimi sation as a single task rather than a collection of tasks
  - Availability of load modules on heterogeneous computing platforms
  - Data exchange and ability to remote log-in from various OS (operating system), e.g. from Windows to Linux and vice versa
  - Parallel scripts for the optimisation process (e.g. population of a GA generation to be distributed and managed on the HPC).

All the above steps are of equal importance and need to be addressed adequately. In this paper, examples will be drawn to both highlight the difficulties and suggest solutions.

1.2 Non-technical barriers

Similar to technical issues, there is also a number of non-technical (organisational and cultural) barriers that need to be over-come, which are outlined in the following paragraphs,

- Organisational issues
  - Access to the right geometry and boundary conditions
  - Lack of user guides, best practice guides, step-by-step guides
  - Lack of training, culture of learning on the job
  - Effective team working
- Cultural issues
  - Importance perceived by the mangers and seniors within the organisation
  - Trust and confidence in the process, allowing for healthy scepticism
  - Accepting the unexpected! (Strange shapes not seen before)
  - Competition with other methods, e.g. manual design
  - Lack of undersigning amongst ‘generalists’ as compared to few specialists
  - Overselling a methodology (one size fits all approach to everything)

2.0 DISCUSSION SECTIONS

In this paper, some of the topics identified above will be expanded with examples drawn from real experiences of the author and his colleagues in industry. Success stories are shared to highlight and offer solution to the above aforementioned challenges leading not only to a successful application but routine adaptation of ADO/MDO in industry.

2.1 Technical issues — tools and processes

The seven key areas that enables the ADO/MDO are mentioned in Section 1.1, a very detailed analysis of each section is out of the scope of this paper. However, some key areas are expanded in the following paragraphs, in order to highlight some of the technical challenges. Companies or departments which fail to utilise ADO/MDO are those which fail to appreciate the importance of each of the seven steps identified in Section 1.1.

2.1.1 Geometrical representations and parametric design

The ultimate aim of the ADO/MDO is to produce efficiently a geometry that is fit-for-the-purpose, i.e. achieves certain require-ments in an acceptable time frame. Hence, in the core of ADO/MDO is a flexible way of representing a geometry and parametrically altering it to achieve the design intent. A detailed survey of possible techniques are given in Refs 4 and 5, the following three main categories give a summary of available techniques:

1. Geometry representation: e.g. construction of a surface from a cloud of points, or representing an aerofoil by its camber distri-bution and its thickness, plus LE/TE shapes, etc
   (a) Master constructions lines, curves and surfaces, e.g. by spline and NURBS[6] — This can be done inside or outside of the CAD making use of KF (knowledge fusion)[7]
   (b) Polynomials such as NACA & NASA series aerofoil[8,9]
   (c) Orthogonal functions[10]

2. Parametric design, which includes efficient ways of altering an existing geometry either from its first principal components (as given by item one above), or applying bulk changes based on the engineering knowledge, e.g. lean, sweep, stagger and skew changes of a blades, the categories are summarised below,
   (a) Engineering parameters[11]
   (b) Hecks and Henne bump functions, HHB[12]
   (c) Free-form deformation, FFD[13]

3. Topology optimisation, where no initial parametrics are used to define a geometry however, mathematical techniques such as level-sets and distance fields[14,15] are used to manipulate the geometry and/or remove unwanted geometry, i.e. sculpting the geometry.

There are a number of other alternative techniques that can be used to parameterise a given geometry, arguably based on a hybrid combination of techniques presented above, for example, the PDE (partial differential equation) approach and CAD-based approach. Bloor and Wilson[16] have presented a compact method of parameter-izing the surface geometry of an aircraft using 4th order elliptic PDEs. The advantage of the approach is that a 3D surface can be parameterised in terms of a small set of design variables. The idea was extended to turbomachinery blading by Harvey *et al*[17].

ADO/MDO will not produce both useful and interesting results if the geometry is not defined and altered in an interesting† and smart way. For example if a blended wing is an optimum solution for a given flight mission, then how can we define a design space based on combination of a cylindrical fuselage based on a centre and radius with a cross-section of a wing based on sectional data which excludes blended wing as one if its design candidates?

Although the perturbation functions such as (HHB) are constructed to have smooth and orthogonal properties, they have two distinct disadvantages: for one, the engineers using them usually do

† *Although not scientific, by interesting it is meant that ADO can produce a range of geometry which could be potentially useful and allow the designers to see alternative designs which could be potentizally useful and allow the designers to see alternative designs which they may not naturally think of.*

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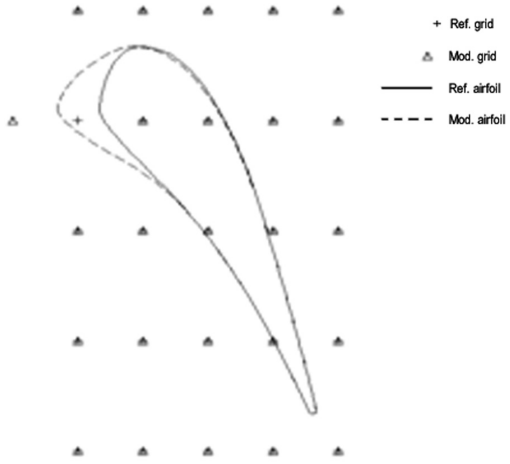


Figure 5. FFD control box (5 x 5) — LE extension for a turbine blade.

not have a 'feel' for how to apply them to the datum geometry and secondly, control of curvature may be difficult, especially if the desire is to apply them locally, e.g. at or near the LE/TE. Exporting the modified geometry back to CAD/PLM could also be challenging, which may require reverse engineering the NURBS surfaces.

Both the control points of a NURBES curve and/or its weights can be used as design parameters, however, even a crude representation of a surface by 30 × 30 (u-v) control net, leads to 1,800 design freedoms (e.g. if each point is allowed to move in two directions), clearly this would be impractical to be used in an optimisation loop. Similarly, the control-net of a FFD box can lead to a very large number for design parameters, hence, research is needed to group those points to move together, see Fig. 5. There has been some promising foray into this topic based on PCA (principal component analysis[18] (to group and reduce the number of active design parameters). The PCA or POD (proper orthogonal decomposition) identifies a combination of design parameters which are the most energetic, in terms their influence on cost functions and constraints, searching an equivalent design space with a much reduced number of parameters is beneficial to the optimisation process, however, on the other-hand in practice it has been found that different parameters affect different figures of merit at different part of the design!

Related to this issue, readers should be aware that there is a fine balance between the number of design parameters, the quality of solution sought and the computer resources available. If the number of design parameters is sensibly reduced, the computing cost would go down and chances of getting a more smooth geometries also goes up, on the other-hand a reduced degree of freedom could translate to a stiffer problem for the optimiser to produce any improved solutions, in Ref. 19 it is shown that increasing the design space (spline points defining an annulus line of a compressor by five points) would lead to better results that is actually better than a hand-design one, whilst the reduced design space could only produce results that were inferior to those obtained by the hand-design process.

CAD packages have come a long way from being treated as a drafting tool but be useful as a design tool. However, it should be noted that certain disciplines due to historical and legacy reasons don't make use of CAD as the starting point to generate a solid model, e.g. the turbomachinery aerodynamicists start to generate a blade sections from velocity triangles and their experience on how to use a camber and thickness distraction based on normalised shape functions. There exits a pre- and post-CAD world. Hence, translation is needed to pass the geometry from one discipline to another which could be quite tricky, often requiring de-featuring lets say going from a manufacturing models (many hundreds of constructions lines and curves) to a CFD model. The meshing tools used with the simulation technique also require watertight geometry, hence often repairs of geometry are needed. In this case compatibility of tolerances in different packages could also have significant importance. Hence, tools such as Rhino3D[20] and CADFix[21] are used to either repair or defeature a geometry which could be quite time consuming. There is also a possibility of linking to CAD directly (via an API) to access the geometry and hence avoid some of the aforementioned translational problems[7].

The use of the commercial CAD systems for geometry modelling can potentially save development time and be the single source for all geometry construction and manipulation i.e. the so-called Master-Model. The Intelligent Master Model[22-23] is particularly attractive as it allows scaling of various components automatically to achieve a desire goal. However, the nature of 'hot' or 'cold' representation of a blade or 'running' and 'un-running' of a fan blade due to exertion of the centrifugal forces and gas loads means that it is quite challenging to hold one definition of the geometry as a Master Model that controls every component in the engine. Furthermore, the number of design freedoms for such a master model that control the whole of a modern aero-engine made up of thousands of components will be so large that it makes the optimisation of the whole engine intractable. In practice a subset or subsystem needs to be isolated to be optimised within given constraints.

It should be noted that the Master-Model method of generating parts has little ability to control a part's topological outcome. An important observation about feature-based CAD construction is that the resultant geometry may not be explicitly defined in any branch of the Feature-tree[24]. This has implications in aerodynamic design using adjoint methods (requiring gradient sensitivities) or mesh perturbation methods requiring topological consistency.

To summarise, there are many different ways of generating and manipulating a geometry, each having its own advantages and disadvantages, before embarking on an optimisation task, one needs to carefully assess the design requirements bearing in mind the availability of the tools on all the computer platforms that ADO/MDO will be run. Upstream of any optimisation task it would be sensible to conduct some parametric design to make sure a wide design space can be generated robustly.

2.1.2 Simulation tools

Accuracy and robustness of the simulation tools such as CFD, FE, and impact analysis are of key importance to the engineering community. Whether a design is done manually by analysis or automatically, care must be taken not to mislead the optimisation direction. Considerable research over three decades have resulted in an arguably a set of maturing codes that are routinely used by the design-by-analysis community. Thorough review of these techniques is outside the scope of this paper.

The ADO and MDO makes use of the simulation codes in a batch mode. Nowadays all the COTS and in-house developers appreciate that although GUIs help the user-friendliness of their tools, the codes need to be run automatically in batch with little or no user intervention. The issues to be addressed however are the availability of all tools on heterogeneous computing platforms, e.g. running under the Linux and Windows OS and exchange of data between disciplines, or ADO must cope with codes that are only available on a particular platform. The coupling of CFD and FE (e.g. as needed for flutter simulation or conjugate heat-transfer) is not trivial and a number of surface mapping mesh interpolation techniques (e.g. based on RBF (Radial basis functions) have been developed[25,26].

Although in a modular set-up, simulation tools can be regarded as separate codes compare to the optimisation library tool-box, there are intrusive schemes that are designed to help the optimisation process. Adjoint technique[27,28] falls in this category. Since the cost of obtaining the gradients of the objective function becomes independent from the number of design parameters, it suits cases where the number of objectives and constraints are far smaller in

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comparisons to the number of design parameters. It should be noted that total cost of optimisation still goes up as the number of design parameters goes up as it takes effort to build the Hessian matrix needed for a quadratic (optimisation) convergence. A successful adjoint-optimisation requires the following key steps to be taken,

- Adjoint CFD should be maintained to the same standard and validation as the base CFD (e.g. by at least a full-time, one-person support)
- Generation of the adjoint code should be made as automatic as possible, e.g. by operator overloading available for a C++ code or the same Makefile compiling the non-linear, and linear codes should also create the adjoint code, automatic differentiation helps here
- A library of useful differentiable functions (to be used as the objective function and constraints) should be coded and be ready of the shelf
- Formulate objective/constraint functions in a differentiable form, e.g. the maximum temperature in a disk could be changed to a temperature less than an upper value
- Readers should be aware that a gradient-based optimisation can get trapped in a local minima, hence, global or at least mid-range meta-models that are enhanced by the adjoint gradients, e.g. co-Kriging needs to be developed and seamlessly linked to the adjoint gradients
- Readers should be aware that if the non-linear solver does not converge well, e.g. to the machine accuracy (for example for separated flows), then errors can creep into the adjoint formulation, this can mislead the optimiser

2.1.3 Post-processing, data-reduction and automatic meshing

Post-processing is usually done as part of a CFD simulation to assess the flow field and identify important flow features, in an optimisation process the data usually needs to be reduced to a single number that will help rank a design and/or establish the feasibility of a design. Care needs to be taken to avoid introducing interpolation errors and to provide a consistent set of data to compare like with like, e.g. a passage average pressure loss at a set distance away from the blade TE, even if the blade is swept back. Incorrect post-processing/data reduction can mislead an optimiser, for example, extracting loss on a constant axial plane when blade is allowed to move axially, or mixing losses that occur when the post-processing domain is moved outside the computational domain, hence the apparent loss reduction is simply a re-distribution of loss. Post-processing needs to be consistent with the CFD solver.

The subject of robust meshing in the context of ADO/MDO is too large to cover it in this paper. Interested readers are referred to a number of references available on this topic[11,29]. It should be noted that it is one of the seven major steps in ADO mentioned in section 1.1. It is true to say that for complex geometry, engineers spend more time preparing the geometry and meshing than the time taken to do the analysis on an HPC cluster. There has been a number of efforts to address this, such as 'templating meshing'[11] or a fully integrated mesh generator and flow solver[14].

2.1.4 Advanced optimisation methodologies

In an accompanying lecture note[2] the author has shown the trend in design by analysis is to increase the fidelity of the simulation tools (in order to capture the physics better), the fact that more CPU resources are needed to conduct many runs simultaneously, and the trends in computing capacity towards the Peta-Exa Scale computing.

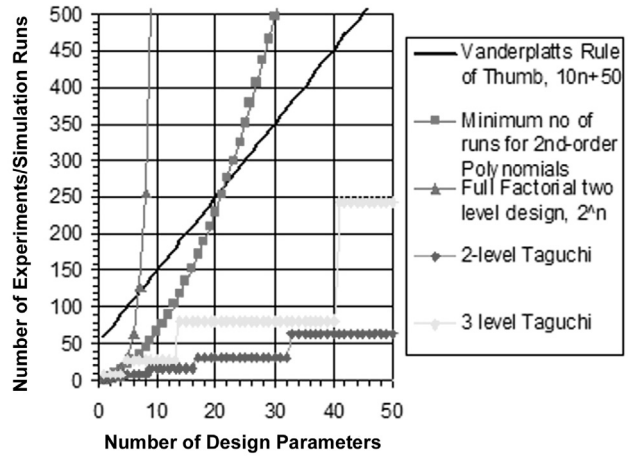


Figure 6. Minimum number of simulations needed as a function of design parameters and DoE technique.

However, ADO/MDO put additional demands on resources. One possibly two orders of magnitude more CPUs than the design by analysis approach is needed. Depending on the complexity further n^2, possibly n^3 numbers of runs are needed, where n is the number of design parameters under considerations, see Fig. 6. The cost is justified because the quality and robustness of the final design should be better than a sequential hand-design, the optimised design is obtained at a much-reduced wall clock-time, and not least the computing hardware is generally cheaper than the man-hour cost of an experienced designer‡. As will be discussed in Section 2.1.5, in the next few years, new multi-core CPUs and GPUs (graphic cards) will give a further speed-up the analysis-time by 10-15 times of what they are today, it is argued a smart optimisation could also give a similar speed-up in the design search time. For example, on a range of complex analytical test cases as well as a large industrial test cases, a method based on the mid-range approximation (MAM) is shown to outperform a range of other optimisation algorithms commonly in use today[2]. Working with university research centres the techniques are modified and made robust to deal with occasional simulation failures such as non-converged CFD results and noisy functions. Factor of ten speed-ups achieved already is quite significant and is the difference between a 'go' and 'no-go' decision as regard to utilising optimisation at all on a given problem.

Hence, it is proposed that further research is needed to increase the capabilities of the search algorithms even more, especially for large-scale optimisation problems. Compared to the improvements in HPC hardware, this new generations of 'smart' algorithms will give similar if not more speed-up in the ADO/MDO process. Working with universities engaged in this activity like Rolls-Royce's UTC arrangement, it is beneficial to share and define industrial challenges to focus the academic activities. We (including industrial seniors and academic professors of other disciplines) should also get away in thinking, optimisation algorithms are trivial (compare to lets say solution methodologies for Navier-Stokes equations) and can be found in the back of a numerical recipe book!

Today, most high-fidelity CFD-based ADO problems reported in the literature have involved design parameters typically fewer than 50, however, as the fidelity of the simulations increase, components need to treated together as subsystems leading to the Virtual Engine, VE (simulation and design) capability[2]. The VE approach means the number of active design parameters could rise to over 1,000, as Fig. 6 shows the curse of dimensionality acts a real barrier to conduct a thorough search of the design space, the implications is that a global optimum or feasible solutions could not be found.

‡ *E.g. £80 per hour = 800 cores at 10 pence per core per hour.*

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2.1.5 Work-flow and data management

Establishing a workflow that can be run automatically is an essential part of the ADO/MDO process. A series of commodity frameworks such as (iSIGHT[30], Model Centre[31], DOT[32]) and the Rolls-Royce in-house SOFT[33] graphical user interfaces (GUIs) are designed to facilitate and allow user to visually 'program' a required work-flow. An important part of the process is the file-parsing capability, as well as creating loops and nested loops, as needed. Common look and feel GUI reduce the cost of training and leads to better take-up by the end-user, hence some COTS vendors are producing concepts such as Workbench[34] (that allows for MDO in one framework), or open source platforms such as Paraview[35] is used to produce a common GUI for pre-and post-processing and work-flow automation. However, in the author's experience, most complex systems require more adaptive linkages (e.g. file parsing), which is achieved by scripting. Scripts are usually done in simple shell scripts or more advanced languages such as Python, Pearl, etc. In some cases the scripts could become complex, made of many thousands of lines. The bespoke nature of these scripts mean that they are often not generic and case dependant, which makes the task of their support quite taxing. Standards and best practises need to be defined to facilitate the deployment of ADO/MDO to the end-users and make it as seamless as possible, otherwise lack of standardisation in scripts is a barrier to ADO take-up.

Lack of integration and automation expertise in the end-user's departments can hamper the take up of ADO/MDO. Hence, training is needed to avoid usage of ADO/MDO by a few 'specialists' and propagate amongst the generalists. Equally, further work is needed to make the simulation tools easier to operate in batch and optimisation-friendly. International standards (such as STEP, CGNS, etc.) need to be followed to produce better inter-disciplinary simulation tools. In the absence of universal adherence to such standards, Simulation-tools' developers need to openly share the definition of their I/O data formats and/or to undertake to maintain reverse compatibility of the users' interfaces. Most ideally the subroutines that read and writes the data structure should be publicly available.

Each CFD simulation usually generate gigabytes of data, ADO/MDO, would create multiple instances of the data which needs to be stored, curated and analysed to extract the required information. Hence, data management is the backbone of such modular but coupled system. The scientific community needs to reduce significantly the effort needed to store, search, and access and reuse this data, otherwise the data management becomes an unnecessary distraction. Efficient data fusion and data mining from variety of sources are the key requirements of the data management system that ADO will make use of. The data traceability (tagging) and provenance (linking data points to the data sources and/or meta data that generates them) is important in ADO/MDO to explore the relationship between good designs and the design vector that has produced it. The tracking of data through workflows should be made automatic, and integrated with industrial process lifecycle management tools (such as Teamcenter, Windchill).

2.1.6 HPC needs

High performance computing (HPC) needs for ADO/MDO are summarised below,

- Available hardware capacity (load, speed, and storage): Peta to Exa-scale computers are needed[50] — As analysis get more sophisticated, a large number of long running simulation tools need to be run on the HPC clusters — high fidelity simulations (to better represent the physics) require large scale (multi-core) machines
- Load-sharing queuing systems, e.g. LSF, SGE (Sun Grid Engine), although these are suitable for long running jobs to provide a fair share system, they are inadequate for the optimisation purposes where a number of jobs need to be run per design iterations (e.g. a GA population), hence a more dedicated (ring-fenced) clusters provide a more optimisation-friendly environment, or a scheduling system that recognises optimisation as a single task are needed
- Today engineers make use of heterogeneous computing systems, e.g. high fidelity CFD tools are often run on the backbone of a Linux cluster, whilst other tools such as CAD is only available on the front-ends which could be a Tech-PCs running under Windows OS. A number of problem can arise in this scenario as following, lack of robust ssh, scp (remote secure shell, remote secure copying) because of security issues, lack of automatic log-in (password protected), large amount of data generated almost simultaneously, which needs to be transferred efficiently (CFD simulations often generate Gigabytes of data but their transfer is limited to the band-width of the network), switching off the PC during the night, differences in the use of lower & upper case names, forward and backward slashes, end of the line null character, etc.

The above issues can seriously hamper the ADO/MDO process, hence needs careful considerations. Grid computing (linking disparate computes to form a large one) or Cloud computing (on-demand resource provisioning similar to utilities that can be switched off and on) are being worked on to provide solutions to some of the aforementioned challenges.

2.2 People issues

Today, many engineers are needed to work as a team which is often multi-disciplinary and are not positioned at the same location, i.e. geographically dispersed. The projects are shared with suppliers and risk sharing partners across the globe. In this situation, (useful) communication becomes challenging, making the chances of finding a solution quite hard. In this scenario, it is beneficial to use common set of tools and design practices, as intercultural and language issues also become more problematic, with basic matters like metric/imperial conversion of data having the potential to wreak havoc. Although astonishing, the costly failure of the NASA Mars Climate Orbiter project is attributed to the failure of Lockheed Martin engineers to convert imperial pound/seconds navigation data into metric Newton[36]. On the other-hand the culture of one size fits-all can stifle creativity and lateral thinking, a healthy balance therefore is needed. It is quite interesting that research has shown that there is an optimum number for a given team[37], exceeding this would lead to a reduction in productivity quite similar to the communication over-head in a parallel HPC system!

To a large extent the optimum size depends on factors such as the location of the team members, the task that the team are working on, and the length of time team members have known each other, can surmount the effect of team size. There is a general consensus that as team size increases, there are greater challenges in terms of coordination, and the likelihood that non-co-operative coalitions will form[38] and some research[39] has found that having 'too few' or 'too many' team members can reduce performance (i.e. the relationship is curvilinear). Many researchers have been reluctant to specify exact numbers, as so much of the evidence is inconclusive, but in some areas of the literature it has been suggested that the optimal number of team members may be somewhere between 5-12 team members[40,41] and that there is a genuine drop off in performance over and above 20 team members. This has implications for the size of the team developing and supporting the ADO/MDO applications for the virtual engine.

The traditional way of handling complexity in aerospace organisations is based on divide-and–conquer approach, e.g. an aero-engine is divided into sections, such as fan systems, compression system, combustion system, turbine system, installation, etc. and sub-disciplines, such as aerodynamic, structures, lifing, cost, manufacturing, etc, This division of labour often leads to unproductive competition

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between discipline with their own false sense of ownership of a problem, e.g. compression system 'owns' the last OGV, whilst the combustion system 'owns' the diffuser just before the combustor, whilst in reality an integrated OGV-diffuser- combustor should be used (and if resources allow it turbine's OGV, and blades should also be included) to design various components. The artificial barriers produced in this manner lead to sub-optimal designs. It should be noted that the fact that an engineering organisation has worked well in the past does not guarantee that it will in future as the system gets more complex, MDO needs to be progressed to be applied to the whole engine level and not on a component or just subsystem levels.

Optimisation should be treated a discipline by itself but should not be regarded as 'owned' by a particular engineering discipline or department as it should go across all the sectors. It is vital there would good co-operation across engineering teams and project managers. Experience indicates that significant tensions and/or even cultural differences between senior engineers and project managers can lead to the overall project failures to meet its objectives[42].

It goes without saying that ADO/MDO training is needed to educate not just the engineers the know-how to use the methodologies effectively but also educate their managers of the usefulness of the techniques. Not many universities teach optimisation as part of their mechanical or aerospace engineering colloquium, hence, dedicated, in-depth training is needed. Easy to obtain and relevant information on the Intranet pages should be provided. The culture of 'learning-on-the-job' should be minimised but not eliminated. Learning on the job culture mean that the latest and appropriate tools and techniques won't be used, and the adaptation of such tools are deemed costly, and burdensome overhead. The key to successful deployment is early adopters and local champions that generate Kudos by being the local expert. ADO/MDO is a complex task, this cannot be wholly taught and that on-the-job-learning is an essential adjunct to teaching, hence a good balance is needed.

Having said the above, it is quite unrealistic to expect a designer to be an expert in all the seven subject areas identified as needed for a successful ADO in Section 1.1. Hence, in practice it has been observed that the most successful ADO projects have been when a specialist from the 'Methods Department' works in an integrated-team along side the designers who actually should take a lead role in the ADO application. This way the designer takes the 'ownership' of the ADO process and could become the champion for the ADO process, a good application example can be found in Ref. 43.

2.2.1 Cultural issues

Related to the people's issues identified above, there are other cultural issues that deserve to be mentioned and discussed. Lawrence and Scanlan[42] discuss the reasons why large engineering projects often fail to achieve key goals, like the delivery date and the agreed budget. The aerospace projects are distributed across many departments and often geographically disparate locations, are highly complex, yet the management tools used are very old and basically not fit-for-purpose. They also argue that the problem has been exacerbated by the cultural problem such as resistance to change and/or to use the modern tools that could be made available to them.

Making use of Ref. 44, Lawrence and Scanlan also describe three types of cultures that often exists in large organisations: pathological, bureaucratic and generative. Of relevance to the current paper is that their research has revealed a deep conservatism in the engineering community and some reluctance to embrace new methods. It is found that organisations become used to their own (legacy) tool sets and find it difficult to give up established practices and familiar software products. This phenomenon has also been described by others as NIH (not invented here) syndrome. In the bureaucratic culture new ideas create problems whilst in a generative culture new ideas are welcomed. In the generative culture engineers are encouraged to actively seek information and rewarded whilst in a bureaucratic culture messengers although are listened to not acted on, messengers are not trained and attending conferences are referred to as 'jollies'. Desirable cultural features revolve around openness, honesty, knowledge sharing and trust. An innovative company develop a learning culture where employees are encouraged and rewarded for attending conferences and are receptive to new ideas and change.

Lean, international companies that need to compete in a global market have definitely eliminated the NIH syndrome from their work force. People have understood in order to survive, they need to embrace both change, and diversity as fast as possible. However, when it comes to ADO/MDO there are other cultural issues that could act as powerful barriers, the two most common ones are: the concern and sometimes fear that people can be replaced by machines, hence, cost-saving statement that if a process can be speed-up by 20%, 20% of the workforce can then be eliminated rather than saying 20% of workforce can do more innovative work faster. The problem has stemmed from the 'black-box' approach to ADO/MDO, not realising engineers are at the heart of the decision making, such as definition of cost functions, and constraints, and assessing the quality of solutions that ADO/MDO can provide.

Competition is another area where ADO/MDO is treated with dislike rather then embracing it as a tool amongst many other tools in the arsenal. The author has come across many cases where arbitration is sought to decide whether a hand-design is superior to an alternative design obtained by the automatic optimisation process. This is fair as any process that produces multiple solutions needs arbitration, pre ADO, arbitration has been applied to multiple hand designs. However, the arbitration should be fair, unbiased and done for the right reasons i.e. be objective (aiming for the lessons-learnt) where the 'goal-posts' are not changed during the process. This sort of competition is not healthy and does not encourage "team-working".

2.2.2 Lack of trust

Engineers by nature are curious people wanting to know how a design is obtained and why, all in minute details. Hence, MDO is often treated with suspicion when a final good design is obtained going from A to B, without knowing all the steps in between that an optimiser has taken and why! The following statement from Belie[45] from Lockheed Martin nicely captures this: 'MDO seems to be a suspicious mix of magic, hope and hype all wrapped in a tidy, yet unverifiable, black box'. As mentioned above this stems from the impression (not fact) that the human designers are taken out of loop, whilst the best success stories for MDO is when a creative team is able to articulate a complex problem, freeing them from conducting tedious multiple iterations themselves, hence, concentrating on understanding and interpreting the good designs.

It is also argued that the simulation tools are not mature enough to be used in an automatic way by a 'dumb' optimiser! However, it is quite ironic that the same tools are used by the designers as a collection of 'black boxes'. At least in ADO the approach in systematic and errors are quantified. Fortunately, in ADO absolute exact figures of merit are not needed, but ability to rank the designs accurately is the key, hence as long as the optimiser is not completely mislead, useful solutions can be obtained. For example, part converged solution on coarse meshes can be successfully used in the course of optimisation[46], however, towards the end, higher fidelity meshes and modelling and tighter convergence are needed to verify the results.

2.2.3 Strange shapes

Human beings are generally afraid of the unknown, including the strange shapes that they have not seen before. This can lead to lack of trust and acceptance of 'stranger' geometries. Hence, there exists a strong conservatism. The nature of aerospace designs have been

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Figure 7. Lockheed F-117 Nighthawk, first flown June 1981.



Figure 8. Silent Aircraft Initiative — the Cambridge-MIT Institute design.

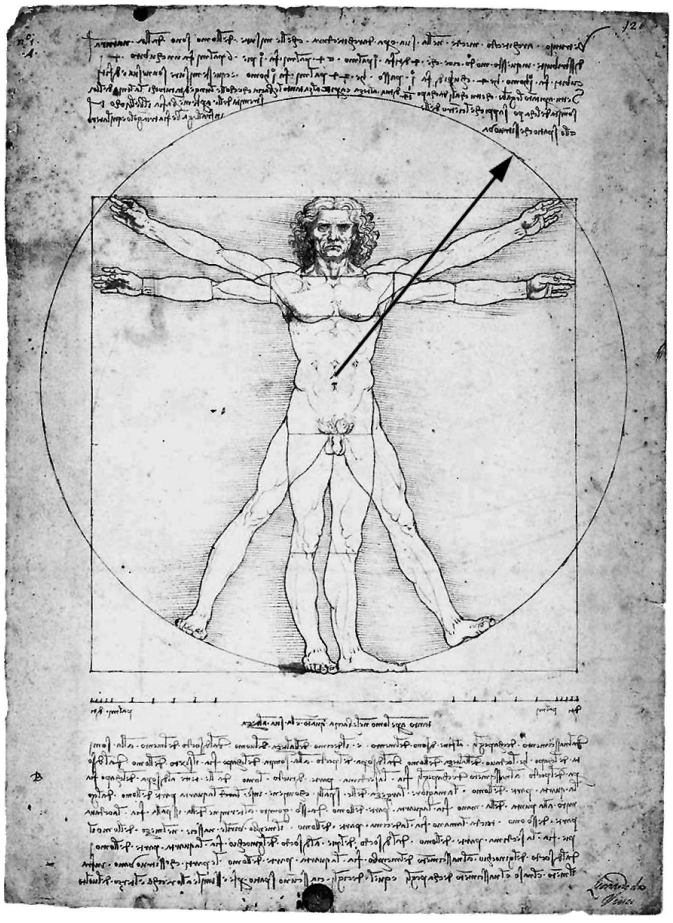


Figure 9. Golden section ratio applies well to da Vinci's Vitruvian Man.



Figure 10. Symmetrical pattern of a Persian rug.



Figure 11. Picasso's painting of a lady.

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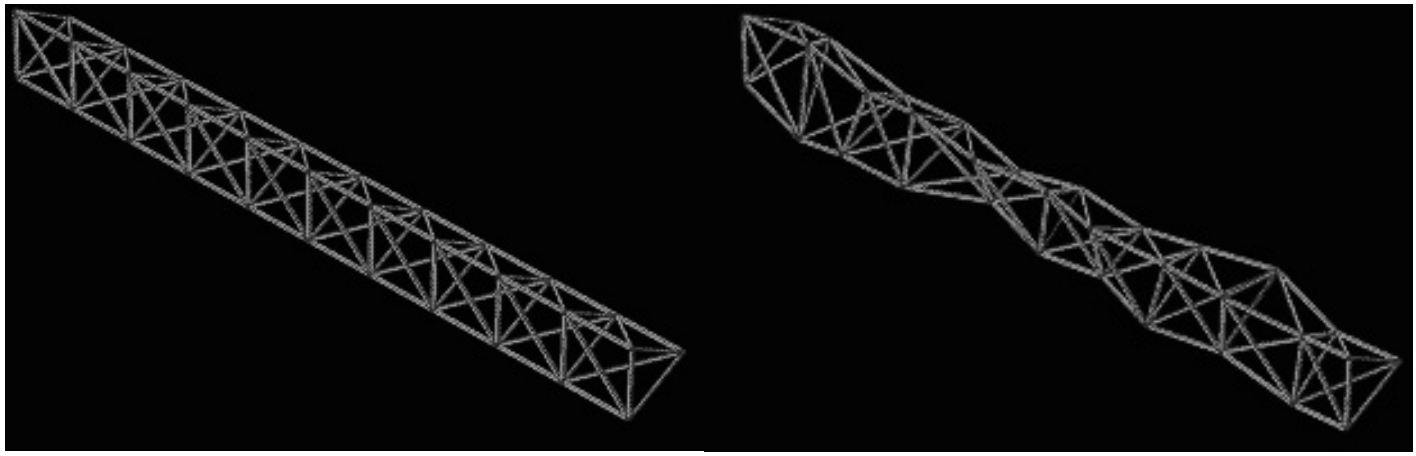


Figure 12. Datum and optimised satellite boom, tested at Southampton University[48].

evolutionary and not revolutionary, most passenger aircraft today looks the same as aircraft designed in the '60s: a cylindrical fuselage with two wings sticking out, the high bypass ratio family of aero-engines whether two shaft or three shaft almost looks very similar.

It is true that necessity is the mother of most inventions, strange shapes produced for stealth fighter/bomber (shown in Fig. 7) developed during the cold war arguably is the manifestation of a very strong requirement to stay undetected, a similar requirement could lead to strange shapes for the 'green-aircraft' of futures, see Fig. 8.

In the engineering design there is a common understanding that 'If things are right, they look right'! This may be a strange notion that a number of arguably good aerodynamic designs based on solving the Navier-Stokes equation are rejected because they don't pass the test of the eye.

Human eye is very quick to detect change in gradients of a geometry (basically curvature variation, similar to shadowgraphs in experimental fluid dynamics), basic aerodynamics tells us that the static pressure variation directly relates to this, and hence the state of the boundary-layer etc. From stress point of view sharp corners and turning should also be avoided! Although, the engineers past experience is extremely valuable, the reason for the above judgment could have non-scientific and perhaps evolutionary reasons. In literature, the golden divide ratio (also refer to as divine ratio) (1.61803:1)[††] is mentioned as the 'perfect' ratio between components defining an assembly. There are plenty of examples that fall in this category[47]. Humans also appreciate symmetry, and most 'beautiful' things have natural symmetry, hence most people find fractals and symmetrical repeat pleasing to the eye, e.g. the Persian carpet shown in Fig. 10. Of course, arguably, there are exception to this rule, see Fig. 11.

As mentioned in Section 2.1.1, it is extremely important to have a flexible design space, and global optimisers (if allowed) will explore the design space outside the previous experiences and can produce shapes that do not conform to any previously-seen. Figure 12 shows such a shape based on a numerically optimised three-dimensional boom for satellites[48]. The optimised geometry has better vibration frequency modes (as tested in the lab) and yet deviates from a regular, symmetrical shape.

It is also quite possible to obtain turbomachinery blades that does not pass the 'test of the eye' yet have better performance, e.g. the stator blades, shown in Fig. 13, as part of a high fidelity CFD-based optimisation have much better aerodynamic performance compared to the base blade (as tested in the lab)[49]. Arguably, lack of constraints in the optimisation process could produce a shape that is perfectly optimum for one discipline but not the other one. For example, for structural reasons the blades may not be able to sustain the end loads or even the gas loads on them. Hence, it is crucial to include all the necessary disciplines in the optimisation process, leading to MDO and not just ADO. Never-the-less, it seems the aerospace design is evolutionary and very much conservative rather than revolutionary, as Fig. 14 illustrates, however, the technology advancements (with time)

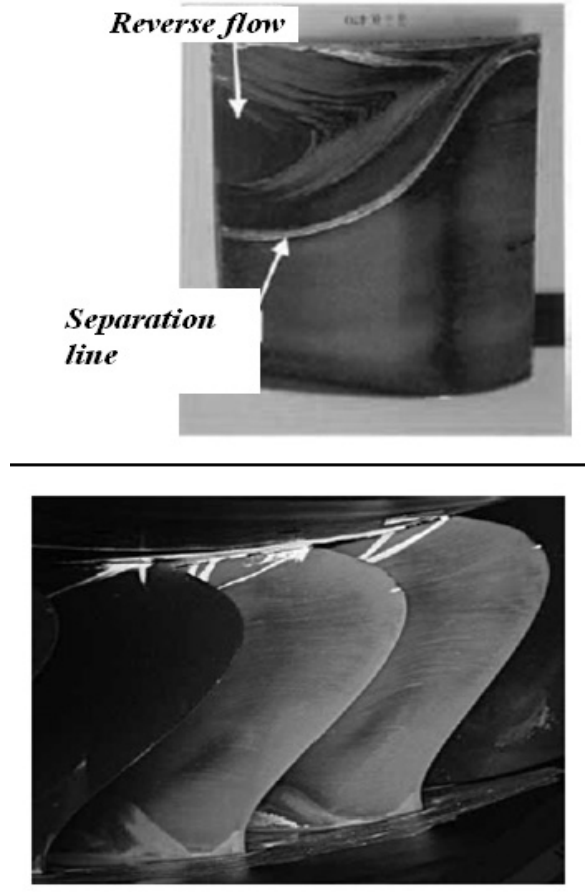


Figure 13. Datum and optimised stator blade tested at the Whittle lab, Cambridge[49].

often takes the form of a 'S' shape; as we reach the plateau region on top, a 'jump' or step-change in technology is needed to meet the challenges set for the design community. Arguably the topology optimisation will help in this endeavour.

2.2.4 Not overselling the ADO/MDO

Sometimes people who advocate the usage of ADO/MDO inadvertently causing it a great disservice by overselling its capabilities. The author has attended many engineering meetings, where quite hard problems such as 'un-running' a geometry and FE-CFD couplings are

[††] $\Phi = (1+\sqrt{5})/2$

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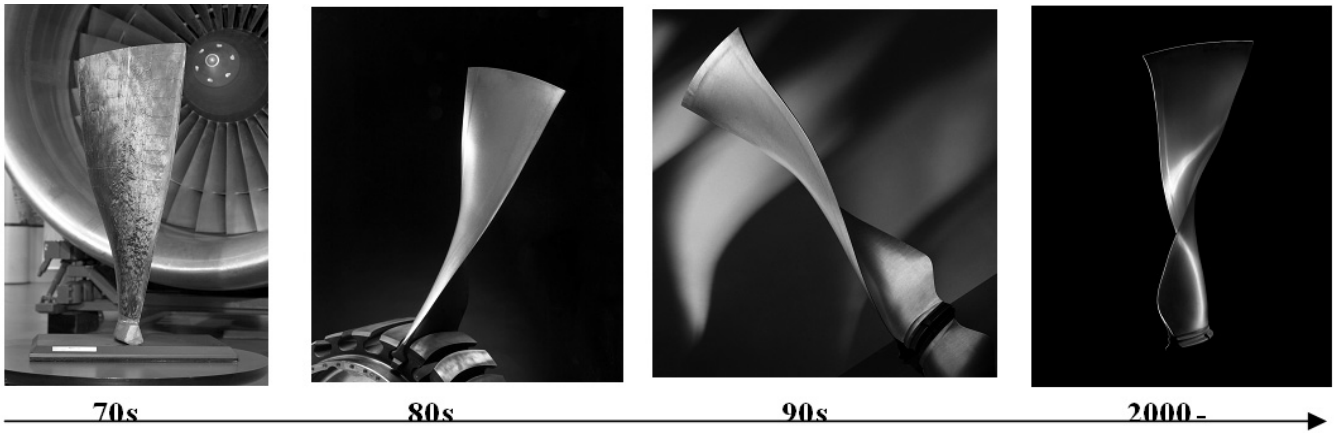


Figure 14. Evolution of jet engine fan blades over time.

mentioned to be easily solved by just using a software that provides work-flow management and/or an optimisation library whilst the automation of the simulation tools, interpolation of solutions from different sources onto disparate meshes, and 'hot-to-cold' geometry translations have very little to do with being able to search a design space efficiently, adequately and of course automatically. Work-flow management is not the same as multi-disciplinary coupling. It is well known that one of the main benefits of ADO comes from the automation itself, even without doing any optimisation.

It is well known that (if not careful) optimisers will exploit the weakest point in the design process. Although, exposing such weak links is beneficial, ultimately leading to a much more robust system, in the midst of design (specially if fire-fighting), the last thing you would want to do is to tell your chief engineer that you have obtained no improved solution because the mesh generation does not work robustly, or the problem is not formulated correctly, and further constraints are needed to produce a practical design or your HPC queuing system is not adequate for automatic optimisation. In promoting ADO/MDO, it should be remembered that confidence is hard to gain, but easy to lose!

A series of pilot project needs to be carefully crafted and conducted leading to the best practise solutions generated and published for future use (ready and off-the shelf, as described in Fig. 1).

3.0 CONCLUSIONS

Automatic design optimisation (ADO) has not had the anticipated impact in the turbmachinery design. The intent of this paper is to highlight the problems & challenges facing the engineers who would like to apply ADO and MDO technique to aid the design process to take corrective actions. The challenges are both technical and organisational/people related.

Over the past 20 years, considerable research has been done on techniques needed to conduct automatic optimisation in order not to replace the human designer but produce a valuable tool that would aid the design process. Resources and planning are needed to address the technical, cultural and organisational barriers that have been identified in this paper.

It is extremely important for the companies to recognise the importance of all the seven technical steps identified in this paper and make sure adequate, resource and funding are available for research and development in all seven areas. Although, not explicitly defined in all sections of this paper, the key to success in ADO/MDO is to conduct a series of pilot studies and recognise that upstream 'pre-work' is needed to make sure people-processes and tools are at the 'production' technology-readiness-level.

It should also be recognised that attention to the ADO technology and tools by itself is not enough, non-technical issues related to the human factors and organisational issues carry equal weights and deserve special considerations. The following three rules apply to a successful deployment of ADO/MDO,

- Find an early adopter who will champion the new technology,
- Be prepared to suspend all new development work and concentrate solely on supporting the nascent user base,
- Success breeds success — ultimately you have to be offering users something they want. It's amazing how previously strongly held objections and prejudices can be quickly abandoned in the face of success.

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