Preliminary Multi-Disciplinary Optimization in Turbomachinery Design

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Abstract: The gas turbine engine is a complex aerodynamic machine with performance, structural and manufacturability challenges. This paper gives an overview of a multidisciplinary optimization approach applied to the conceptual design of small aircraft engines. A description of major turbomachinery disciplines and the numerous interactions between disciplines is given followed by a discussion of the need for preliminary design optimization. The approach to development of such a system undertaken at Pratt & Whitney Canada is described including identification of appropriate design tools and their influence on the geometrical definition of an engine cross-section. Finally, preliminary optimization results are presented.

1 INTRODUCTION

Over the past five decades, the gas turbine engine has evolved rapidly to provide a reliable and efficient business solution for global transportation. The engine design process is clearly a large contributor to this evolution. This process is highly iterative, multidisciplinary in nature and complex. The success of an engine depends on a carefully balanced design that best exploits and considers the interactions among the numerous traditional engineering disciplines such as aerodynamics and structures, as well as the life cycle disciplines of cost, manufacturability, serviceability and supportability. A crucial task in the engine design process is to define a concept because "the best engineering effort cannot totally right a poor concept selection" [Ref.1]. Employing multidisciplinary optimization (MDO) at the conceptual phase of design is important, since it is at that stage that the largest influence on the final product is realized. In this paper, the application of MDO methodology to the conceptual stage of the design cycle will be referred to as Preliminary Multi-Disciplinary Design Optimization (PMDO).

Over the last few years, the increasing complexity of engineering systems has stimulated progress towards developing an MDO capability and implementing it into the design process. The concept of MDO can be interpreted as a formal methodology that facilitates exploration and exploitation of interdisciplinary interactions to achieve a better overall system. The earliest MDO developments occurred in the 1970s and have been progressing ever since, revealing great potential to improve product quality and significantly reduce development time, thus, helping the product to remain competitive in a global market.

Current industry applications of MDO include biomechanics, automotive, electromagnetics, nuclear, electronics and, also, aerospace where the interest in MDO has been particularly intense. An extensive survey of MDO applications in aerospace design has recently been presented by Sobieszczanski-Sobieski and Haftka [Ref.2]. This paper identifies the main challenges of MDO implementation as being computational cost and organisational challenges which are being

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addressed by developing various approximation and decomposition strategies. Another paper by Sobieszczanski-Sobieski [Ref 3] describes five MDO conceptual components: Mathematical Modelling, Design-Oriented Analysis, Approximation Concepts, Optimization Procedures, System Sensitivity, and Human Interface.

In an effort to solve engineering optimization problems, a number of promising MDO methods have been developed. These include the All-in-One (A-i-O), Individual Discipline Feasible (IDF), Multidisciplinary Feasible (MDF) [Ref. 4], Collaborative Optimization (CO) [Ref. 5], Concurrent Sub-Space Optimization (CSSO) [Ref. 6], and Bi-Level Integrated System Synthesis (BLISS) [Ref. 7] methods. To address the problems of limited computational resources and to analytically substantiate the practical applicability of MDO methods, a two-phase study has been conducted on the performance of a selected set of MDO methods that included MDF, CO, IDF, and BLISS methods at the NASA Langley Research Center. A comparison of the performance, classification of the methods, guidelines for using specific methods and systematic method testing procedures are presented in Refs. 8 and 9.

In any type of MDO applications, the efficient solution of the problem depends greatly on the proper selection of a practical approach to MDO formulation. Six fundamental approaches are identified and compared by Balling and Sobieszczanski-Sobieski [Ref.10]: single-level vs. multi-level optimization, system-level simultaneous analysis and design vs. analysis nested in optimization, and discipline-level simultaneous analysis and design vs. analysis nested in optimization. From the results presented therein, two conclusions are apparent: 1) no single approach is fastest for all implementation cases, and 2) no single approach can be identified as being always the slowest. Therefore, the choice of approach should be made only after careful consideration of all the factors pertaining to the problem at hand.

With the increasing acceptance and utilization of MDO in industry, a number of software frameworks have been created to facilitate integration of application software, manage data, and provide a user interface with various MDO-related problem-solving functionalities. A list of frameworks that specialize in integration and/or optimization of engineering processes includes: iSIGHT (developed by Engineous Software), ModelCenter (developed by Phoenix Integration), Epogy (developed by Synaps), Infospheres Infrastructure (developed at the California Institute of Technology), DAKOTA (developed at Sandia National Laboratories) and many others. An extensive evaluation of select frameworks has been performed at NASA Langley Research Center. The report by R. Krishnan [Ref. 11] presents a number of primary requirements for the "ideal" framework, describes the positive and negative aspects of each of the evaluated frameworks with respect to those requirements, and recommend frameworks that deserve a closer look. Additional detailed descriptions of MDO framework requirements are provided in Salas and Townsend [Ref. 12].

A significant amount of MDO research has been conducted in the field of turbomachinery design. A number of reports have been published presenting the development of optimization environments [Refs. 13 and 14], optimization methods, and procedures for turbine engine design. Particular aspects of multidisciplinary optimization for different turbomachinery design stages are investigated by Dornberger et al. [Ref. 15]. The differences in the optimization approaches and methods used in preliminary and final design steps are also shown. The present paper describes the ongoing work related to the development and implementation of a MDO environment with a focus on its application to the conceptual design of the gas turbine engine.

2 TURBOMACHINERY DISCIPLINES

Overall Design Process

The process of engine design starts at the aircraft level. As depicted in Figure 2.1, an engine is a system that seamlessly integrates into the larger system of an aircraft. Engine design is a top-down procedure in which two processes, design and manufacturing, start and proceed from opposite ends of the system configuration. The design process starts at the overall system level and gradually moves down to the component level. The manufacturing process proceeds in the opposite direction.

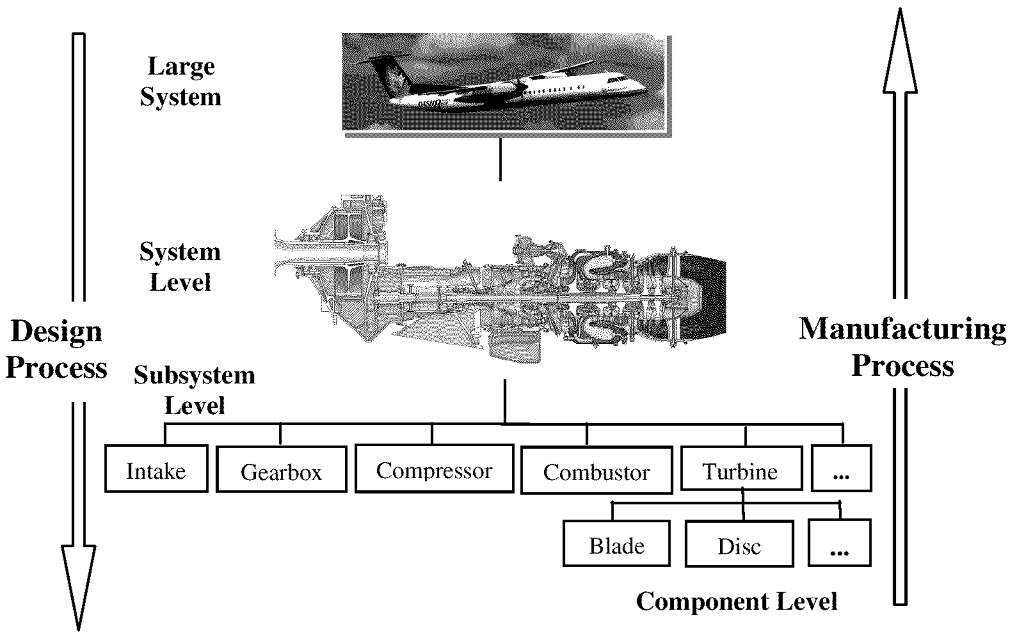

Figure 2.1: Design and manufacturing processes [Ref.16]

The efficient and reliable integration of design and manufacturability aspects of a project has been the focus of Concurrent Engineering (CE). Concurrent Engineering can be defined as a systematic approach to concurrent design of products in which all disciplines, including manufacturability and supportability, are addressed simultaneously. A comprehensive definition of the CE concept is provided in Ref. 17. An example of the implementation of the CE approach for turbomachinery applications is the Agile Engineering Design System developed by Concepts ETI, Inc. The potential benefits of the Agile system for the turbomachinery design process and the latest developments in the field are presented by Japikse in Ref. 18.

Traditionally, the design of the gas turbine engine follows three major phases: Conceptual Design, Preliminary Design, and Detailed Design that involves designing for manufacturing and assembly. As was stated in the introduction, the scope of this paper is the conceptual phase of the design process which involves the exploration of different concepts that satisfy engine design specifications and requirements.

The gas turbine design is a sequential and highly iterative process that is represented by a net of tightly coupled engineering disciplines. The interaction that takes place among the disciplines is a series of feedback loops and trades between conflicting requirements imposed on the system. The complexity of the process is depicted in Figure 2.2. A close-up view of the process that takes place within the discipline of aerodynamics is shown in Figure 2.3.

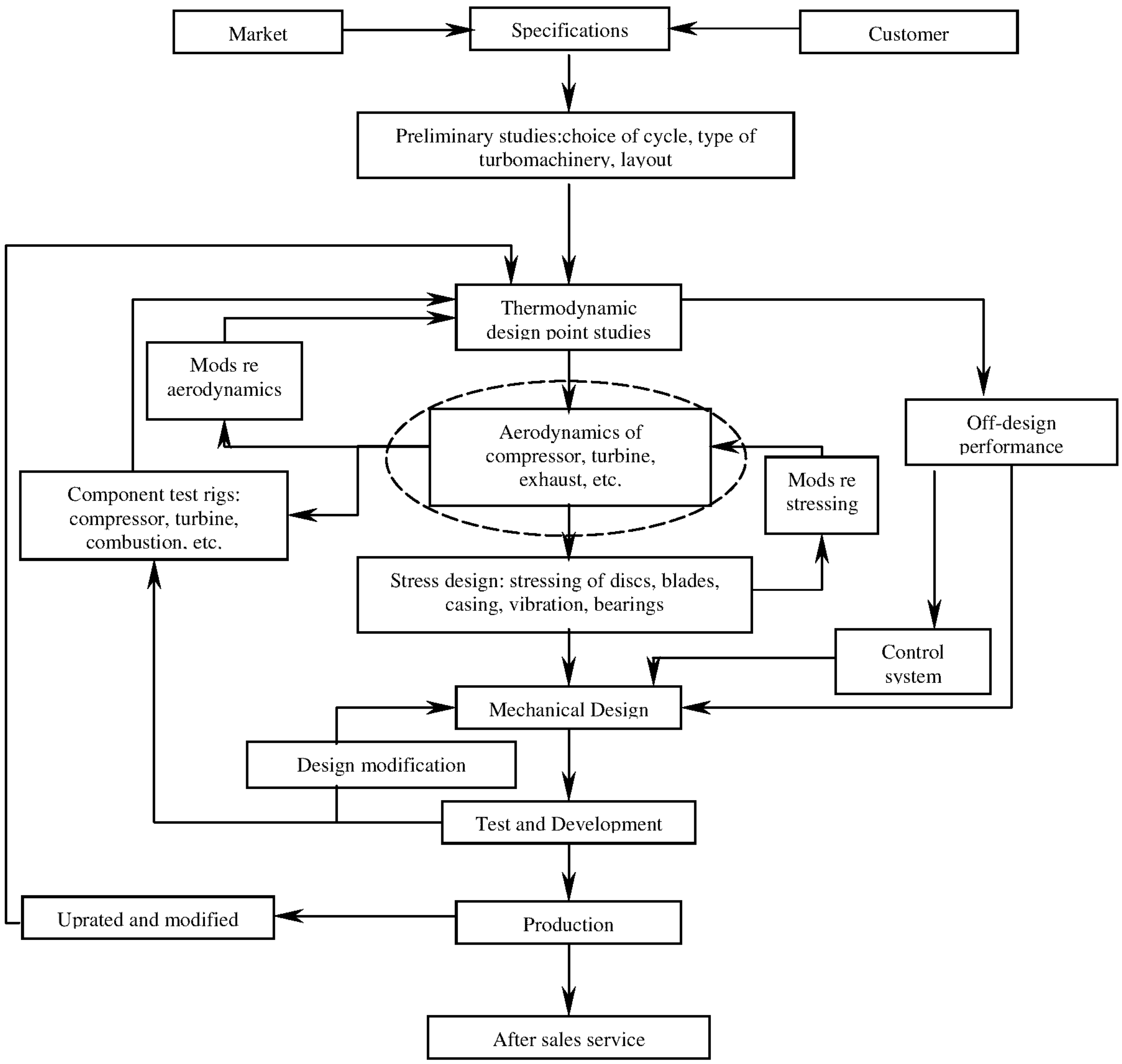

Figure 2.2: Gas turbine design steps [Ref. 19]

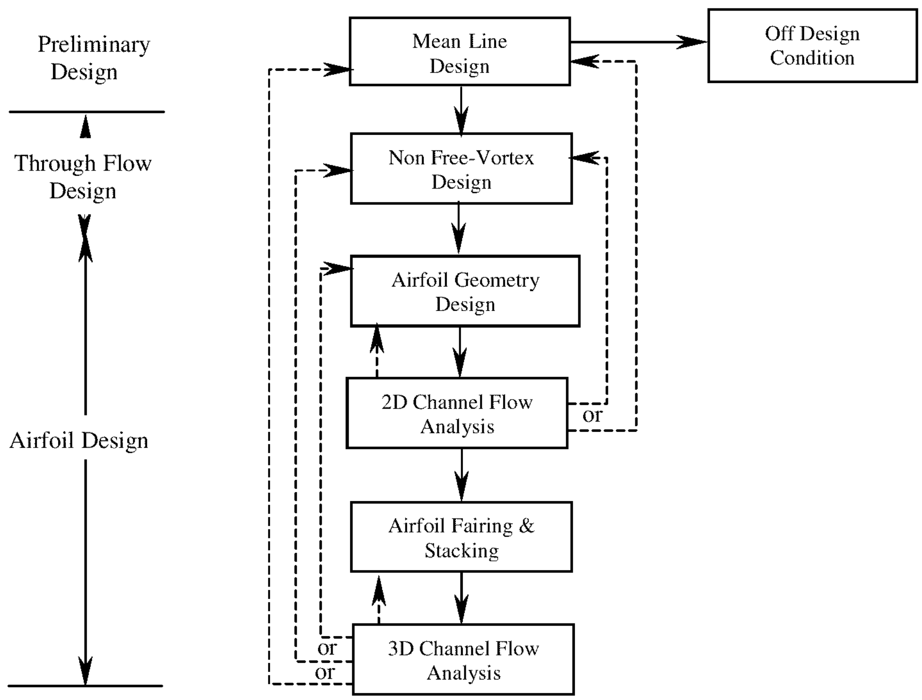

Figure 2.3: Aerodynamic design process

Every design must be grounded in sound physical principles that are grouped into categories named disciplines [Ref. 1]. Figure 2.4 illustrates the hierarchical breakdown of an engine into different engineering disciplines that govern the design of major engine components that, in turn, combine to make the final product.

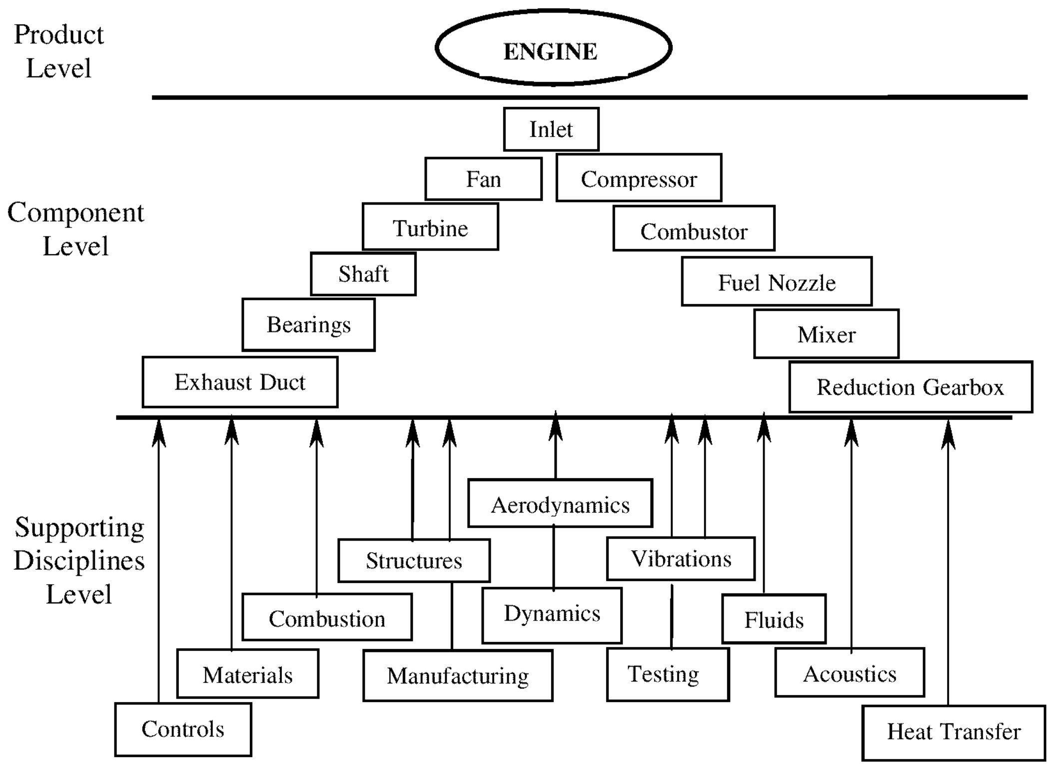

Figure 2.4: Product, components and the supporting disciplines

Interactions Between Disciplines

At the Concept Design stage of an engine, the aim is to develop a concept far enough to be able to estimate with reasonable accuracy the feasibility, weight and the potential production and development cost. This information is used directly in formulating a proposal to the Aircraft manufacturer. In such an advanced system as an engine, the couplings among disciplines are numerous and strong, requiring a multidisciplinary approach to design. The performance of the system depends on harmonious interaction of these disciplines and components that must meet a large set of strict operational requirements and standards. A typical list of parameters usually addressed in the Concept Design Study, and the supporting groups involved, include the following:

1. Basic requirements – Marketing and Customer
2. Thermodynamic cycle – thrust, specific fuel consumption, maximum temperature, pressure, etc. - Advanced Performance Group
3. Installation requirements - Fluid Systems Group
4. Compressor and Turbine definition - Compressor and Turbine Module Centres
5. Materials available and their allowable limits such as temperature, creep, oxidation, strength, low cycle fatigue life capability, and buckling limits - Materials Engineering Group
6. Weight - Product Definition and Weight Groups
7. Air and Oil systems - Fluid Systems Group
8. Manufacturing cost targets and factory standard cost - Product Cost Group
9. Envelope requirements - Design Groups, Customer and/or Nacelle Engineering Group
10. Direct operating costs - Customer Support
11. Manufacturing limitations - Manufacturing Engineering Group

A perfectly balanced design requires all of the above factors to be considered and selected appropriately. There are inherent contradictions between some of the disciplines that make this task difficult. The thermodynamics dictate that parameters that make an engine more efficient (e.g. higher operating temperature) are exactly the opposite of what is required for low cost. Materials capable of operating at high temperatures imply higher development costs as well as use of more advanced manufacturing processes which are, therefore, more expensive. Alternatively, introducing turbine cooling also increases the cost due to manufacturing complexity. The same applies to weight. Lower weight for a given performance requires stronger or advanced light alloy materials, which in general are more expensive. One should not be surprised that current solutions may not be optimum because there is insufficient time to carefully study the interactions between the variables which, generally, are the responsibility of numerous disciplines.

Issues with the technical interaction between disciplines

Over time, the way Concept Design studies are conducted has changed significantly. For many years, a single department (Advanced Engineering) was involved in defining the concept using established rules of thumb, simple 1-Dimensional analysis and past experience. This was followed by the involvement of the groups responsible in the end for bringing the concept to production. In this manner, there was little interaction between Advanced Engineering and the downstream disciplines. Engine concepts were therefore proposed with relatively low effort up front and resources were added as the development program proceeded. This process resulted in end-loaded engine development, where changes to the design in the detail design and development phases were time consuming and expensive.

The model of product development in use at present in P&WC is somewhat different to this.

A larger portion of the work is expected to be done up front, in the Advanced Design/Concept stage, with a smaller increase in resource usage during the detail design and development. Figure 2.5 illustrates the old procedure for engine development versus the current system.

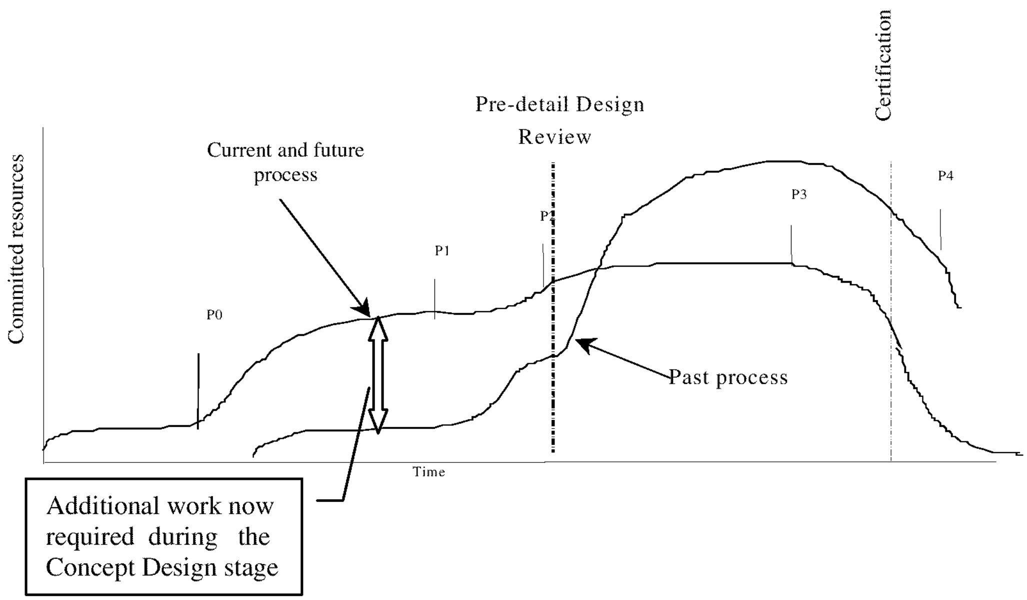

Figure 2.5: Resource usage in a typical engine development program

Since the amount of effort at the Concept Design stage is now much greater than before, the burden could not be carried entirely by the Advanced Design group. A process, which evolved therefore, was to involve the specialist groups directly in the Advanced Concept work. This would potentially avoid downstream redesign. However, it results in significant delay of the concept evolution. The Advanced Design group was expected to deal independently with each of the specialist disciplines, obtain the required input and re-assemble the data into the study and make the required association between the individual inputs in terms of effect on the overall performance, installation envelope and design features. Because the specialist disciplines work with more detailed, such as 2-D and 3-D methods, the results were obtained in a time-scale not commensurate with the time for the concept study and have to be re-inserted into the study manually. A good design is optimized considering all of the parameters above, it is quite clear that interaction between the disciplines must be highly ordered and highly efficient to produce answers in the required time. Many of the parameters or groups are bypassed in the decision-making by resorting to rules of thumb and past experience. Conversely, the decision making may be delayed to the point that competitions are missed.

Some of the common problems with interactions of the disciplines are as follows:

1. Tools of the different disciplines, usually, do not have a common file structure
2. No automated system for transferring data
3. Problems with manually transposing data – typos, etc.
4. Traditional exchange of data is by tables and spreadsheets or graphical.
5. Inefficient and unreliable tools.
6. Time consuming. (Other discipline not available for consultation when needed)
7. Only small areas of the problem are explored because of the time constraint.

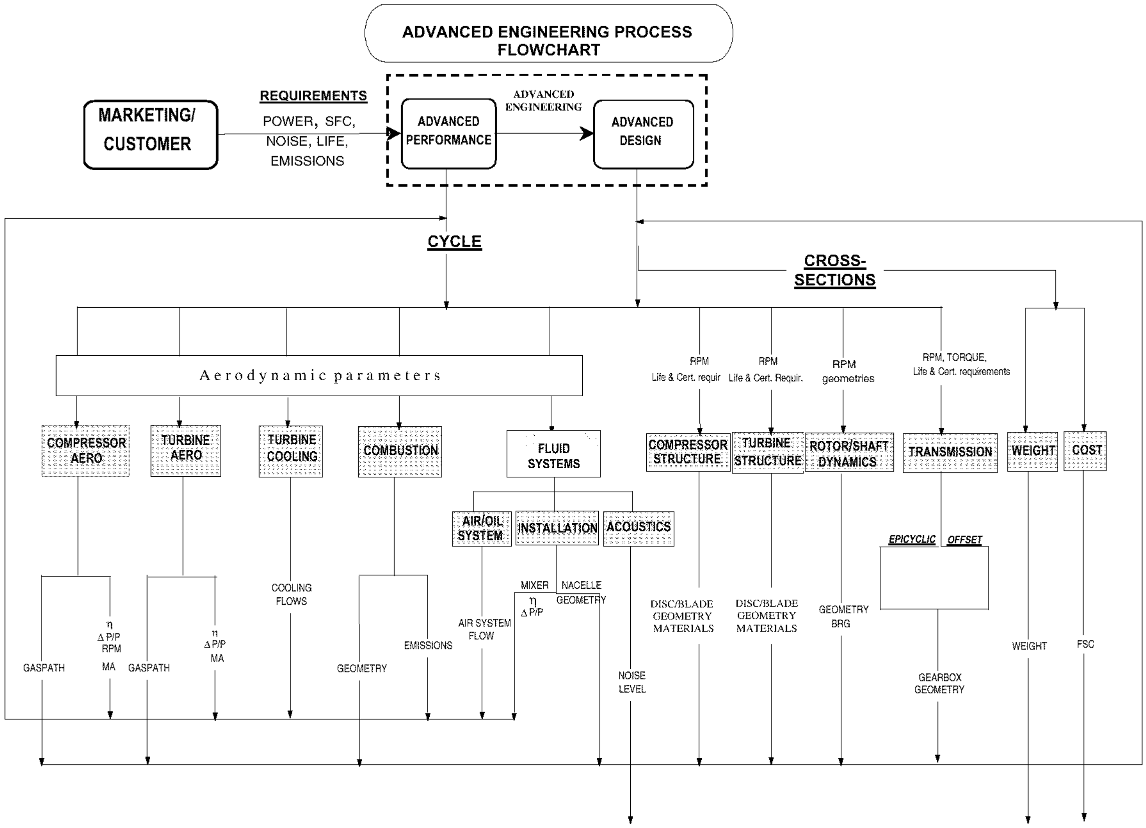

Figure 2.6: Disciplines infrastructure

Figure 2.6 depicts a schematic representation of the infrastructure of the multi-discipline interactions required for a proper preliminary product definition phase in the Advanced Engineering group. This is a simplified chart, whereby data flow between the supporting component groups have not been included to avoid a diagram that is visually unreadable.

3 PRELIMINARY PRODUCT DEFINITION PROCESS

To fully understand the challenges associated with the definition of a preliminary engine configuration, an overview of steps and activities to be performed is required. The design of a new gas turbine engine begins in the New Products Definition group, or “Advanced Engineering” department. It is here that a new powerplant (or a major derivative engine modification) is conceptualized for further follow-on detailed engine definition and hardware materialization. The engine definition in the Advanced Engineering phase normally begins with one of the following circumstances:

- Direct request from a customer (Original Equipment Manufacturer (OEM)) for a new engine to cater to a specific vehicle propulsion need or power generation application.
- Internal company strategic investigation on potential market niche for a suitable powerplant that will fill this gap.

It is from there that the Advanced Engineer will commence a product definition study to conceptualize a new engine to address the request. As will be described, this phase of study applies all the disciplines needed for proper product definition. Each of the disciplines involved has its own domain of design parameters. Moreover, there is no one unique parameter to optimize, but numerous variables and criteria to consider when optimizing an overall combined vehicle/ engine system. Designing a powerplant to best cater to the overall aircraft requirements in itself encompasses a whole realm of engine design parameters that need to be carefully selected and optimized. A classic example of a gas turbine design optimization is the Overall Pressure Ratio (OPR) and cycle temperature selection. The Figure 3.1 illustrates cycle pressure ratio and temperature influence on basic engine characteristics, such as Specific Fuel Consumption (SFC) and Specific Power. OPR and Temperature in itself are linked to other inter-dependent parameters such as component efficiencies, air-system flows, engine weight, durability, cost, etc., all having an impact on the optimum OPR-Temperature selection.

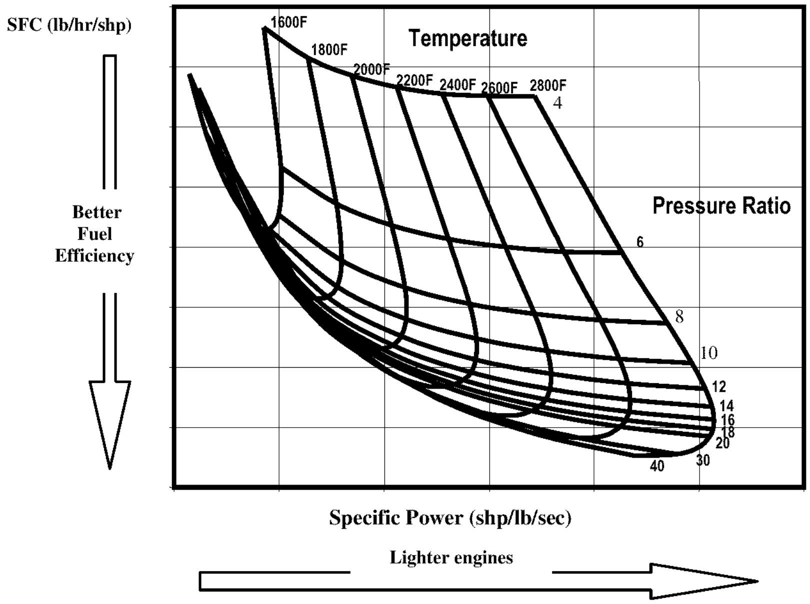

Figure 3.1: Cycle pressure ratio and temperature influence

Other examples of parametric optimization in gas turbine design is the core size optimization as illustrated in Figure 3.2. Maximum power (typically hot day take-off) influences the core size needed to respect the turbine operating temperature limit. Again, a parametric study of this nature will encompass many other inter-dependent parameters influencing the optimum; i.e. air-system flows, component size effects, engine weight, durability, cost, etc. Choosing the right size of the core will need to take all the parameters into consideration.

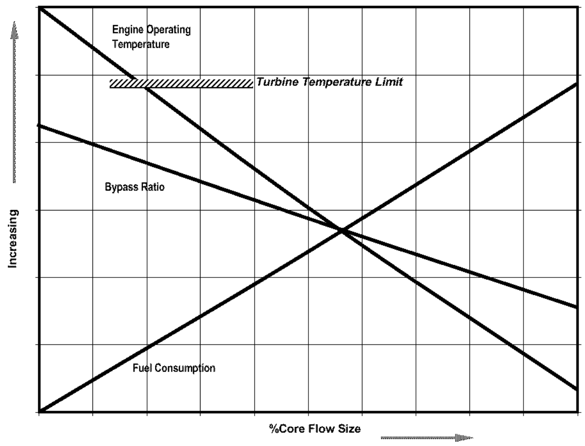

Figure 3.2: Turbofan core size sensitivity

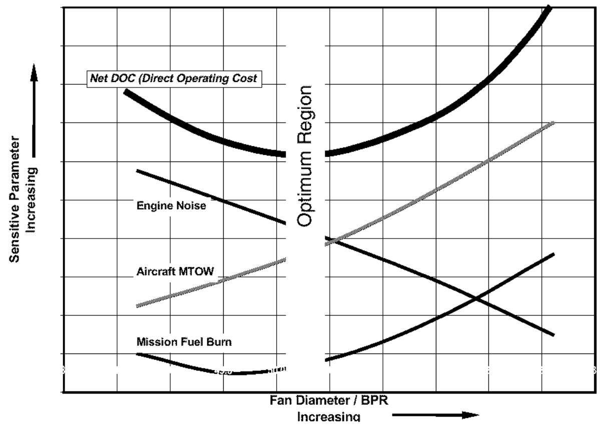

Figure 3.3: Fan diameter/BPR parametric

A good example of a multi-parametric optimization is the bypass ratio (BPR) / fan diameter sensitivity study. An optimization study of this nature typically has many influences on the overall aircraft performance and its associated operating cost (Figure 3.3). Here, increasing the engine fan diameter (higher BPR) will typically improve the engine Specific Fuel Consumption. However, associated with increasing fan diameter is a higher powerplant weight and increased nacelle drag that will inversely impact the overall mission fuel burn. Moreover, the mission fuel burn must also be weighed with the impact of aircraft maximum take-off weight (MTOW), noise levels and ultimately its global impact on the aircraft direct operating cost. As can be seen, optimizing solely on the basis of best engine SFC may not necessarily provide the best for the overall aircraft point of view. Only after considering all the pertinent metrics will the proper optimum be found.

These examples of cycle optimization only touch a few of the many parametric studies necessary to design the best powerplant for a vehicle. Each of the studies will typically involve many disciplines and a multitude of design parameters. There is obviously great potential for process improvement through the creation of an automated multi-disciplinary design system.

Upon receipt of the powerplant requirements, the first technical study involves a parametric "thermodynamic cycle" investigation to establish a viable engine configuration and performance attributes that satisfy the needs of the customer. The cycle investigation, or Advanced Performance study, already encompasses several disciplines. Typically, the following key disciplines will be dealt with during the Advanced Performance activity:

- Compressor aerodynamics (fan, low and high pressure compressors…)
- Turbine aerodynamics (low and high pressure turbines…)
- Air system (particularly hot end cooling)
- Compressor/Turbine structures
- Combustion aerodynamics
- Dynamics
- Weights,
- Cost, etc.

Figure 3.4 illustrates the disciplines involved in an Advanced Performance design study. Numerous variables come into play in the Advanced Performance study that typically include (to name a few):

- Flows
- Temperatures (and work)
- Pressures (and pressure ratio)
- Efficiencies
- Duct losses
- Spool speeds
- Air system...

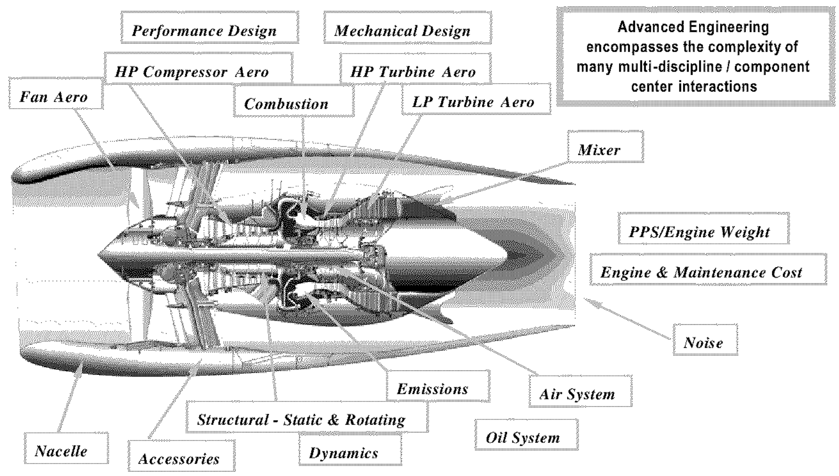

Figure 3.4: Disciplines and components encompassed by Advanced Engineering

An Advanced Performance study requires the analysis and evaluation of individual component performance levels, be it through empirical means or where more critical, a full interactive work process with the corresponding specialist group. With the later, a specialist will analyse/design the component typically using 1-D meanline design tools. When the initial thermodynamic cycle assessment has proven feasible (with the addition of an acceptable business case), a further follow-up Advanced Engineering study is conducted on a more detailed level.

One of the key attributes to be evaluated in an Advanced Engineering study, which follows an Advanced Performance study, is the geometry associated with aerodynamic flowpaths and rotating component discs corresponding to the selected engine configuration (Figure 3.5).

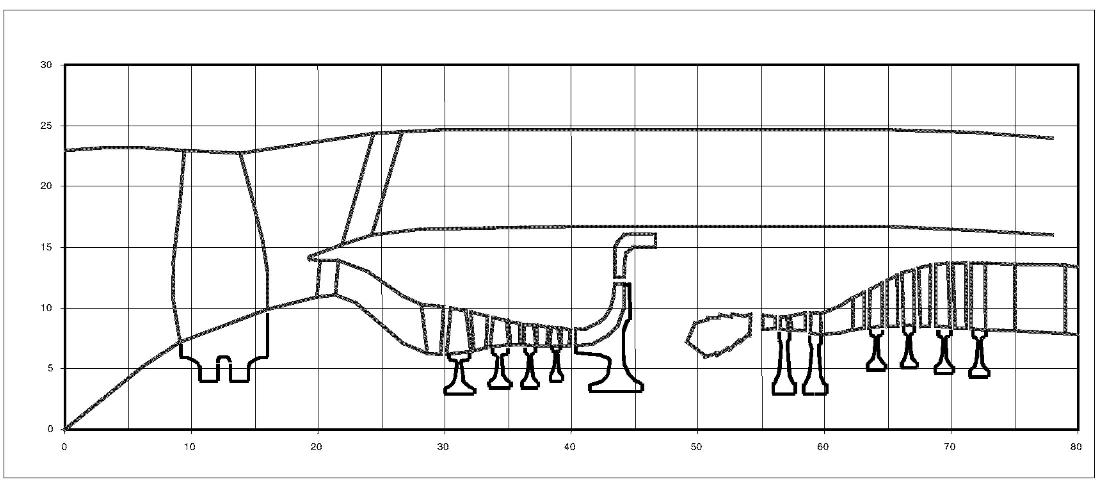

Figure 3.5: Example of geometry assessment

As mentioned in the previous section, the design of an engine starts at the aircraft level. In the aircraft regime, for example, several key criteria that are critical to the optimization and definition of the product include:

- MTOW (maximum take-off weight)
- TOBFL (take-off balanced field length)
- Time to climb
- Mission fuel burn
- Environmental criteria (noise, emission)
- Maintenance cost …

The application, market driving force, vehicle selling attributes, etc. drive the weighting of each of the parameters. Examples of various interactions between the engine design parameters and the aircraft attributes are illustrated in Figure 3.6.

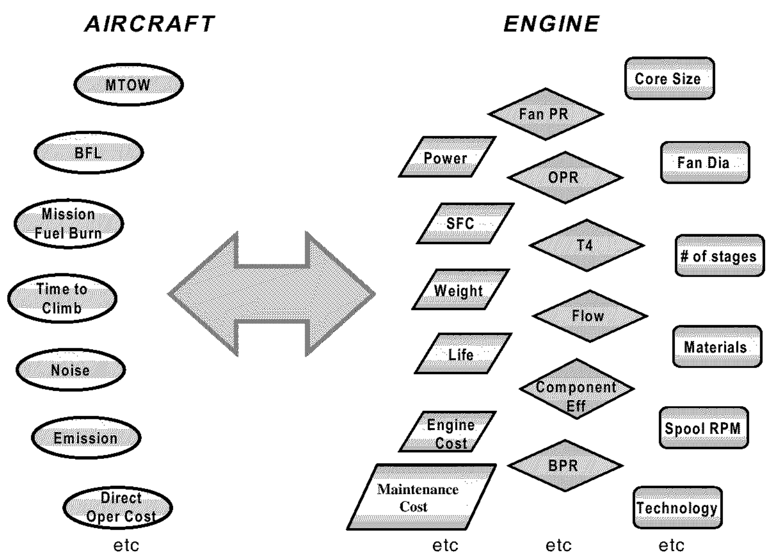

Figure 3.6: Design dependencies between aircraft and engine parameters

Several process levels are evident, each with its own design optimization and all interdependent:

Aircraft

Engine Thermodynamics

Engine components: Aerodynamics / Stress / Dynamics…

Engine Nacelle: Aerodynamics/Mechanical...

Manufacturing

Key deliverables of an Advanced Engineering study include the following:

- Performance
  - Power
  - Fuel consumption
- Emissions and Noise
- Preliminary engine layout/cross-section
- Propulsion system (engine/nacelle) weight

- Factory standard cost
- Estimated aircraft performance:
  - MTOW (maximum take-off weight)
  - TOBFL (take-off balanced field length)
  - Time to climb
  - Mission fuel burn

To fully exploit the best system design, the mentioned parameters require the aircraft/engine design optimization to be conducted in unison and not in isolation. Of course, this can only be most effective with quick data exchange, commonality of tools and fast response rate.

4 THE NEED FOR PRELIMINARY MULTIDISCIPLINARY DESIGN OPTIMIZATION (PMDO)

From the previous sections, it is evident that Advanced Engineering conceptual and preliminary designs encompass a wide field of engineering disciplines and make the largest influence on the final product configuration. Although knowledge increases as the design process goes forward, the freedom to make major design changes decays or causes major delays in the schedule and increased design cost. Therefore, it is of a primary importance that more knowledge is captured in the conceptual phase of the design process in order to avoid problems occurring later in the cycle which require costly efforts to correct.

In general, the concept/preliminary design of gas turbines requires a wide range of factors to be considered and weighed against each other to achieve a viable and competitive gas turbine engine solution. This must usually be achieved in a time scale that is not commensurate with the importance of the task. Thus, decisions are often made with incomplete data and, hence, an increased risk of not meeting all of the design requirements. In the past, it was possible to obtain quick solutions using correlations based on previous engine designs and experience but this will not usually result in an answer of sufficient fidelity for current designs. This method may also lead to data which is conservative by virtue of the fact that the data used is a product of *the way things were* and not the *way things could be*. This can lead to sub-optimal designs and uncompetitive bids in engine competitions. Furthermore, designing in isolation is not viable for a good system design but requires a constant data exchange between the customer and supplier with each expecting fast response to allow immediate reaction for proper design changes to ensure a true optimum system. Another obvious problem with the traditional sequential design approach is the short conceptual phase with unequal distribution of disciplines which does not allow the designer any freedom to improve quality and integrate disciplines for optimization [Ref.20].

Considering the challenges and complex discipline interactions described in previous sections, significant potential benefits can be gained through the incorporation of an automated integration and optimization system. This was the goal of Pratt & Whitney Canada when it initiated the development of an integration/optimization system tool named *PMDO (Preliminary Multi-Disciplinary Design Optimization)* specifically for use in the Advanced Engineering community.

It is the intent at P&WC that Phase I of the PMDO project addresses integration and automation with an optimizer that will quickly generate "Aerodynamic flowpath" results (whole engine) with a follow-up Phase II project to include all basic rotating disc geometry auto-generation. PMDO will be constantly developed and expanded to include additional disciplines (air-system, dynamics, weight, cost, noise, emissions), ultimately leading to the full generation of the engine cross-section (Figure 4.1).

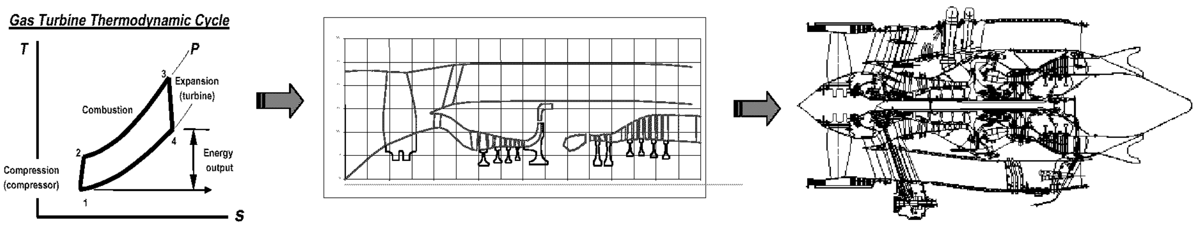

Figure 4.1: PMDO system deliverables

The expected benefits of PMDO include:

- The automated linking of component specialist tools with the thermodynamic cycle program to provide a seamless data transfer with minimal manual intervention
- With the automated link, lead-time for preliminary engine design is significantly reduced
- Reduce the possibility of human error with the elimination of manual data manipulation.
- A more thorough analysis with increased iterations is possible with improved fidelity in design results
- Improved confidence/success level of finding the correct optimum engine design choice

Figure 4.2 illustrates additional goals and improvements in the design process that will be made possible by the PMDO system. The steeper slope of the solid curve reflects that more knowledge will be brought forward to the conceptual and preliminary design phases ensuring that the target engine deliverables are met. Although the time spent in the conceptual phase will increase to capture more knowledge and explore alternative configurations, the time spent in the detailed design will be reduced. The development and implementation of such system is the key to reaping the benefits of improved turnover time and quality of first design during concept study. Thus, the PMDO system will effectively simulate increased resources that are available for the Concept Design stage (Figure 2.5).

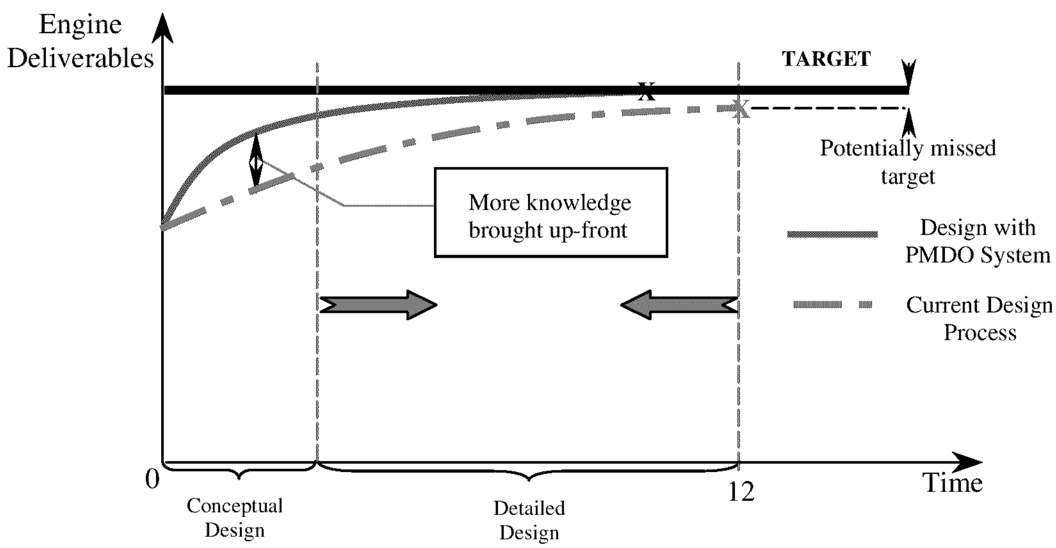

Figure 4.2: Shorten overall design cycle with the PMDO system

5 APPROACH TO PRELIMINARY MULTIDISCIPLINARY DESIGN OPTIMIZATION

The effective introduction of MDO at the conceptual and preliminary design stage depends on adopting the appropriate strategy. Other requirements include adequate information infrastructure and robust design-oriented analysis tools. The use of high fidelity analyses has always been part of the detailed levels of design. The benefits of effective inclusion of high fidelity data into the design optimization process at the conceptual stage have been investigated in the Numerical Propulsion System Simulation (NPSS) project [Ref.21]. This multidisciplinary system of analysis tools enables accurate prediction of propulsion system parameters such as performance and life to be determined in the early stages of the design process. One of the aspects NPSS focuses on is the numerical zooming between 0-dimensional and 1-, 2-, 3- dimensional component engine codes. A detailed description of the development of the NPSS environment and results of a successful zooming of 1-dimensional high pressure compressor results to a 0-dimensional simulation are presented by Lytle [Ref.21] and Follen [Ref. 22]. The approach taken by PMDO is to integrate 0- and 1-dimensional analytical tools of various disciplines. A visual illustration of the location of the PMDO system in terms of the three major elements of complex system simulation is depicted in Figure 5.1.

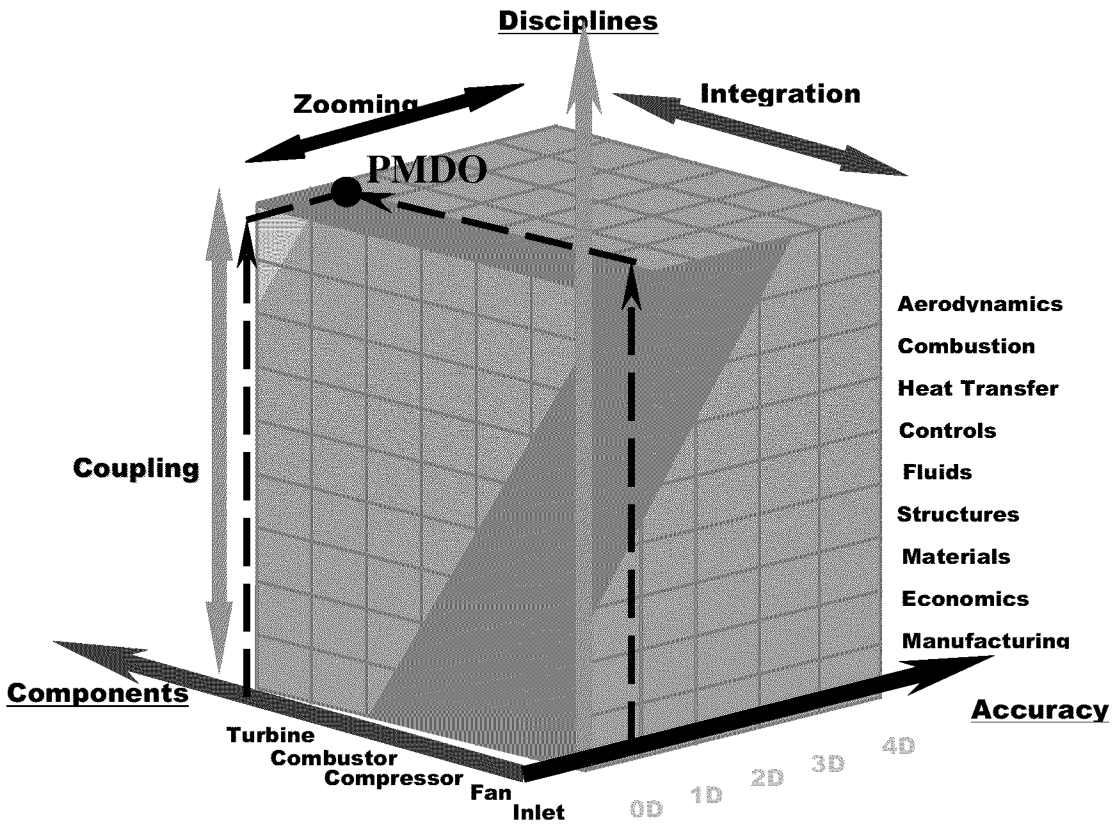

Figure 5.1: Three main elements of complex system simulation [Ref. 21]

The development of an integrated, multidisciplinary optimization tool for the Phase I/II PMDO project is progressing in four steps:

1. Develop a robust tool base
2. Apply single discipline optimization to individual analytical tools
3. Create an integration framework
4. Implement multidisciplinary optimization

The first two steps are well underway and are described with preliminary results. The second two steps are currently being investigated and discussion will be limited to an examination of requirements.

Robust Tool Base

The Phase I/II PMDO project seeks to obtain an optimal engine cross-section (compressor and turbine gaspath and disc shapes) that meets thermodynamic cycle and other constraints at a given design point. Low-fidelity aerodynamic and structural tools (0-D and 1-D) are appropriate for the PMDO project since these tools are robust, execute quickly, and provide sufficient accuracy for the purpose of an advanced engineering study. It is essential that the tools used in optimization are well validated. The optimizer must be constrained to use the tools within their validated ranges so as not to exploit unreliable tool outputs. Higher-fidelity tools (2-D and 3-D) will be incorporated into PMDO in the future to provide additional information to guide configuration decisions.

The aerodynamic characteristics of multi-stage axial compressors and turbines are predicted using 1-D meanline programs in PMDO. Flow prediction in a meanline program is based on the calculation of velocity triangles at the mid-span of the gaspath with empirical models to account for losses. Further information on P&WC meanline programs and loss models is available in Refs. 23 - 25. Typical input to a meanline program includes geometric parameters and engine operating conditions. The output from a meanline program includes a prediction of Mach numbers, pressure ratio and efficiency.

Simple “layout” programs are used to predict the aerodynamic characteristics and geometric cross-sections of fans and centrifugal compressors in PMDO. These programs are based on simple physics, design rules, and audits of previous engines. Losses in ducts such as the engine inlet, bypass duct, and inter-compressor ducts are modeled using either (i) simple correlations with geometric parameters and basic engine operating conditions as input, or (ii) the numerical solution of one-dimensional flow equations with calibrated source terms for blockages such as struts. In the traditional design process, these empirical correlations, “rules of thumb”, and calibrated models have been applied manually. As part of the PMDO project, the rules and correlations are captured in computer programs for inclusion in the automated optimization procedure.

Simple 2-D structural tools are used to size rotating compressor discs and predict the stress and life of discs with minimum weight. Cross-sectional geometric disk parameters, standard fixings, and gaspath shape are combined to define the disc shape. A 2-D analysis predicts stress levels, burst speed estimated on the basis of material utilization factor (MUF), average disc hoop stress, and life based on the stresses at critical areas shape. Airfoil weight, which is used as a boundary condition for the analysis, is estimated based on airfoil cross-section and flow parameters from an aerodynamic meanline analysis combined with empirical data.

Rotating turbine discs are sized using a P&WC program that employs empirical equations that simplify the physical modeling of a rotor from the shroud to the disc. The program includes an airfoil cross-section generator, a fixing designer, and links to a finite element code for disc hub stress evaluation.

Single Discipline Optimization

Optimization with a single tool has been investigated for three cases: axial compressor gaspaths, turbine gaspaths, and turbine discs. In each of these cases, the tool has been linked with an optimizer and successful optimization runs have been accomplished. The purpose of the single-discipline investigations was to:

- Become familiar with the characteristics of various optimization methods
- Determine the best optimization methods for each tool
- Ensure that the selected tools are robust enough for use in optimization
- Explore the effect of alternate sets of optimization variables on convergence and robustness of the solution

The optimizer used for the PMDO project is iSIGHT, developed by Engineous Software Inc. [Ref. 26]. The iSIGHT software is a generic shell environment that supports multidisciplinary optimization. The shell represents and manages multiple elements of a particular design problem in conjunction with the integration of one or more simulation programs. In essence, iSIGHT automates the execution of the different codes (in-house or commercial), data exchange and iterative adjustment of the design parameters based on the problem formulation and a specified optimization plan.

Axial Compressor Gaspath Optimization

A three-stage axial compressor optimization case was run at design point using a P&WC meanline program with the following optimization variables:

- shape of the hub and shroud
- location and corner points of each rotor and stator
- number of airfoils per blade row
- airfoil angles

Constraints were imposed on the following variables:

- diffusion factor
- swirl angle at stator trailing edges
- exit Mach number
- ratio of hub to tip radius
- blade angles
- pressure ratio
- choked flow

The objective of the optimization was to maximize efficiency. The optimization was run for approximately 1000 iterations which took about 1 hour on an HP C-class workstation using a Genetic Algorithm followed by a Direct Heuristic Search. The number of iterations required to achieve an optimum seems excessive and several opportunities are being explored to reduce the iteration count: (i) alternate optimization strategies, and (ii) alternate sets of optimization variables based on "physical" quantities.

The iSIGHT optimizer has a suite of explorative and gradient-based optimization methods that can be applied in any sequence. Different combinations of optimization methods will be investigated in an attempt to improve the efficiency of the optimization process.

The design variables used by the optimizer are expected to have a significant influence on the robustness and speed of optimization. In the current axial compressor meanline application, the optimizer alters the gaspath shape by varying the coefficients of splines representing the hub and shroud curves. The dependence of the compressor pressure ratio and efficiency on the spline coefficients is not direct. An improved set of "physical" optimization variables has been suggested in which the optimizer varies axial distributions of mean radius and area. The advantage of this formulation is that area and radius are "physical" variables that have a direct link to the pressure ratio and efficiency predicted by the meanline program. This direct link should result in a "cleaner" design space, a reduced number of iterations to converge to an optimal solution, and improved robustness of the optimization procedure.

Turbine Gaspath Optimization

A three-stage turbine optimization case was run with a P&WC meanline program in which the optimization variables included the number of airfoils per blade row, the location and cross-sectional shape of each blade and vane, and the shape of the hub and shroud. The only constraint on the output parameters was to keep the Zweifel Coefficient, which is a measure of airfoil loading, constant. The objective of the optimization was to maximize efficiency and minimize the Degree of Reaction which represents the proportion of the static temperature drop occurring in the rotor and, also, reduction in total relative temperature which results in a lower metal temperature for the airfoil. The optimization plan involved three optimization techniques available in the iSIGHT software: Genetic Algorithm followed by Hooke-Jeeves Direct Search Method followed by Exterior Penalty technique.

The results of the optimization run were compared with "baseline" results, as shown in Fig. 5.2. The baseline results were obtained by a turbine design expert in ¾ of a day of dedicated time. In contrast, the optimizer took twenty minutes to set up and two hours and twenty minutes to run on an HP C-class workstation. The baseline solutions are shown as dotted lines in the figure and the optimizer solutions as solid lines. The gaspath shape and number of airfoils per blade row obtained by the optimizer were close to the baseline results. The efficiencies were almost identical with slightly higher efficiencies obtained by the optimizer. Of most significance is order of magnitude reduction in human time required to obtain the solution.

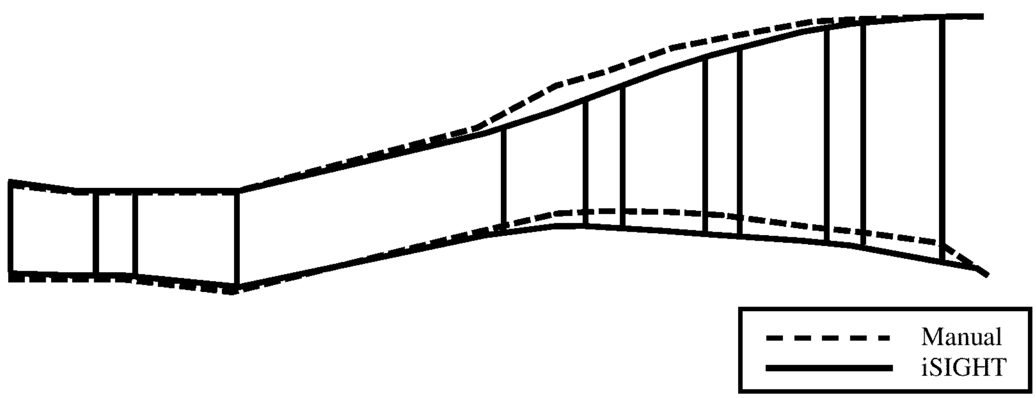

Figure 5.2: Comparison of "baseline" and "optimized" turbine meanline results

Turbine Disc Optimization

The iSIGHT optimizer was linked with a P&WC program used for preliminary 1-D/2-D design and analysis of the turbine rotor discs, as described above. The main objective of the test was to optimize the turbine disc while keeping the airfoil, platform and fixing geometries constant. The problem variables for this particular case included a number of disc shape parameters based on a simplified disc parameterization (Figure 5.3).

The objective of the optimization was to minimize disc weight and maximize burst speed margin. The optimization plan contained three sequential optimization techniques: Genetic Algorithm followed by Sequential Quadratic Programming (NLPQL) followed by Mixed Integer Optimization (MOST). As a starting design point, the optimizer was deliberately given a set of input parameters that generated an unacceptable solution for the disc. The goal of this case was to see how quickly the optimizer could learn about the given design space and obtain a viable design configuration. The first feasible solution satisfying all of the output constraints and objectives was obtained in approximately half an hour on an HP C-class workstation. Relative to a manual design, there was a significant reduction in time required to obtain a feasible solution, the weight of the disc was slightly reduced, and a higher burst speed margin was obtained. Future investigation of optimization strategies will include the use of the Design of Experiments (DOE) to reduce the number of design variables and shorten the time required to converge to a solution.

Integration Framework

In order to automate the design process, an integration framework is required to link the tools in the PMDO project. The requirements for an integration framework are being finalized and several integration frameworks, including commercial products and solutions in development by research groups, are being investigated. A description of framework requirements is given in Ref. 12. The integration framework must satisfy the following requirements:

- automate the transfer of data between tools
- model the links and interactions between all tools and disciplines
- enable concurrent analysis
- allow linking with multiple optimizers
- manage data
- allow automatic execution of optimization involving multiple, user-selected tools
- support task decomposition for multidisciplinary optimization
- have an intuitive Graphical User Interface (GUI)
- be platform independent

Furthermore, the integration framework must be extendable and flexible to meet the requirements of a growing number of tools and disciplines. Future phases of PMDO will encompass additional engineering and economic disciplines and the incorporation of these tools into the PMDO framework in a straightforward manner with minimal effort is necessary. Although PMDO is initially to be used exclusively by P&WC, other UTC divisions such as the Small Military Engine (SME) division will use later versions and the tools of the other divisions will be integrated into the PMDO framework.

Later versions of PMDO will include higher-fidelity tools. The framework must also permit "zooming" [Refs. 21 and 22] to facilitate the selection of a tool with a given level of fidelity for each discipline and include capabilities for transferring data between analyses of different fidelities. As an example of data transfer between data sets of varying fidelity, a feedback mechanism will be included in later versions to allow performance data predicted by the 1-D aerodynamic meanline tools to effect the data in the thermodynamic cycle analysis. The integration framework must allow zooming, feedback mechanisms, and inclusion of high-fidelity tools.

The integration framework must also be compatible with several large development projects that are underway at P&WC in parallel with the PMDO project. These projects include the integration of parametric CATIA V5 geometry and analysis data, as managed by a Product Data Manager (PDM), to form the basis of a Digital Engine. The PMDO system will be integrated into the Digital Engine which will be seamlessly integrated into the P&WC Digital Enterprise. PMDO will both draw data from and contribute data to the Digital Enterprise database. The Digital Enterprise will manage data and make PMDO data available to the rest of the enterprise to be used, for example, as initial geometry and boundary conditions for detailed engineering design.

Multidisciplinary Optimization

Multidisciplinary optimization (MDO) involves the simultaneous optimization of multiple coupled disciplines and includes the frequently conflicting requirements of each discipline. MDO is an active field of research and several methods have been proposed to handle the complexities inherent in systems with a large number of disciplines and design variables [Ref. 2]. MDO can be described as an environment for the design of complex, coupled engineering systems, such as a gas turbine engine, the behavior of which is determined by interacting subsystems. It attempts to make the life cycle of a product and the design process less expensive and more reliable.

The optimization problem is often divided into separate sub-optimizations managed by an overall optimizer that strives to minimize the global objective. Examples of these techniques are Concurrent Sub-Space Optimization [Ref. 6], Collaborative Optimization [Refs. 5 and 28], and Bi-Level System Synthesis [Ref. 7]. Simpler optimization techniques, such as All-In-One optimization (in which all design variables are varied simultaneously) and sequential disciplinary optimization (in which each discipline is optimized sequentially) can lead to sub-optimal design and lack of robustness [Ref. 28].

Various MDO methods are being investigated to determine the most promising methods to be implemented in PMDO. The selected MDO method must achieve the following goals:

- quick turnaround time
- robust convergence of optimization
- convergence to a robust optimum solution

MDO eases the process of design and improves system performance by ensuring that the latest advances in each of the contributing disciplines are used to the fullest, taking advantage of the interactions between the subsystems. Although the potential of MDO for improving the design process and reducing the manufacturing cost of complex systems is widely recognized by the engineering community, the extent of its practical application is not as great as it should be due to the shortage of easily applied MDO tools.

6 CONCLUSION

In the gas turbine engine design process, the multitude of requirements, criteria and competing objectives can be effectively managed with a system that supports process integration and multidisciplinary optimization. An integrated MDO system will be of most benefit at the conceptual design stage since it is at this stage that the greatest impact on the final engine configuration is made. The approach to the development and implementation of such a system at Pratt & Whitney Canada is described in this paper.

The goal of the initial phase of PMDO is to create a system that uses 0-D and 1-D tools to automatically generate compressor and turbine gaspath/disc cross-sections that are optimal with respect to given objectives and constraints. The expected benefits of the initial phase of PMDO include automated data transfer between analytical tools, improved turnaround time, reduced design costs, and improved designs.

The development of a robust tool base is the essential first step in the development of a multidisciplinary optimization system and this first step is well underway at P&WC. An understanding of optimization characteristics and requirements is being attained through investigation of optimization on individual discipline tools and this understanding will be applied to multidisciplinary problems. Further work is underway to examine the effect of alternate optimization variables and algorithms on the convergence and robustness of optimization. Investigations into integration infrastructures and various aspects of multidisciplinary optimization such as decomposition have also been initiated.

Future phases of PMDO will include additional disciplines and higher-fidelity tools. The effective inclusion of high fidelity data into the optimization process at the preliminary design level using numerical zooming will be investigated in future phases. An additional area of future research is the use of approximation techniques to accelerate optimization.

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