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THE ARCHITECTURE AND APPLICATION OF PRELIMINARY DESIGN SYSTEMS

Fabian Donus
MTU Aero Engines
Munich, Gemany

Stefan Bretschneider
MTU Aero Engines
Munich, Germany

Reinhold Schaber
MTU Aero Engines
Munich, Germany

Stephan Staudacher
Institute of Aircraft Propulsion Systems
Universität Stuttgart
Stuttgart, Germany

ABSTRACT

The development of every new aero-engine follows a specific process; a sequence of steps or activities which an enterprise employs to conceive, design and commercialize a product. Typically, it begins with the planning phase, where the technology developments and the market objectives are assessed; the output of the planning phase is the input to the conceptual design phase where the needs of the target market are then identified, and alternative product concepts are generated and evaluated, and one or more concepts are subsequently selected for further development based on the evaluation. For aero-engines, the main goal of this phase is therefore to find the optimum engine cycle for a specific set of boundary conditions. This is typically done by conducting parameter studies where every calculation point within the study characterizes one specific engine design. Initially these engines are represented as pure performance cycles. Subsequently, other disciplines, such as Aerodynamics, Mechanics, Weight, Cost and Noise are accounted for to reflect interdisciplinary dependencies. As there is only very little information known about the future engine at this early phase of development, the physical design algorithms used within the various discipline calculations must, by default, be of a simple nature. However, considering the influences among all disciplines, the prediction of the concept characteristics translates into a very challenging and time intensive exercise for the pre-designer. This is contradictory to the fact that there are time constraints within the conceptual design phase to provide the results. Since the early 1970's, wide scale efforts have been made to develop tools which address the multidisciplinary design of aero-engines within this phase. These tools aim to automatically account for these interdisciplinary dependencies and to decrease the time used to provide the results. Interfaces which control the input and output between the various subprograms and automated checks of the calculation results decrease the possibility of user errors. However, the demands on the users of such tools are expected to even increase, as such systems can give the impression that the calculations are inherently performed correctly. The presented paper introduces MTU's preliminary design system Modular Performance and Engine Design System (MOPEDS). The results of simple calculation examples conducted using MOPEDS show the influences of the various disciplines on the overall engine system and are used to explain the architecture of such complex design systems.

NOMENCLATURE

ACARE	Advisory Council for Aeronautics Research in Europe

BPR	Bypass Ratio
CFD	Computational Fluid Dynamics
CG	Center of Gravity
FB	Fuel Burn
FD	Total Engine Drag
FD_{ref}	Total Engine Drag of reference engine
FEM	Finite Element Method
FN	Net Thrust
LPT	Low Pressure Turbine
$MOPEDS$	MOdular Performance and Engine Design System
$NPSS$	Numerical Propulsion System Simulation
OPR	Overall Pressure Ratio
$PMDO$	Preliminary Multi-Disciplinary Optimization
PPS	Propulsion System
$RRAP$	Rolls Royce Analysis Program
SFC	Specific Fuel Consumption
$TERA2020$	Techno-economic and Environmental Risk Assessment
$VITAL$	EnVIronmenTALly Friendly Aero Engine
$\frac{\Delta h}{u^2}$	Aerodynamic loading
ν	Hub to Tip Ratio

INTRODUCTION

The development of a new aero engine is a market driven decision typically initiated by one of the two following scenarios. First the demand results from the decision of an aircraft manufacturer to develop a new aircraft and second the reengening of marketed aircrafts to decrease the direct operating costs for the airlines. In contemplation of modern marketed aero engines it is striking, that almost any todays engine is developed by a consortium of at least two partners. Apart from the specialization of some manufacturers on certain engine components this is also caused by the wish to share development and marketing risks. In order to minimize these risks a sophisticated product strategy has to be evolved at the beginning of every development. As depicted in Figure 1 this includes the concurrent conduction of market research, technology development and design studies. These studies are conducted to determine a number of engine configurations and designs which are to be persued further. According to Halliwell [1] this is the primary objective of the conceptual design phase. Initially the engines are modeled as pure performance cycles. Considering, that finding the optimal engine design is a multi-disciplinary process, which can only be solved by taking into account the various other design disciplines such as *Aerodynamics*, *Mechanics*, *Weight*, *Cost* and *Noise* means are needed which allow to account for all interdisciplinary dependancies. Within the detailed design phase each of these disciplines is accounted for within seperate specialty departments in a more or less consecutive manner. In order to account for the interdisciplinary dependancies this process is iterated until a design is found, which satisfies each of both, the technical and the economical constraints.

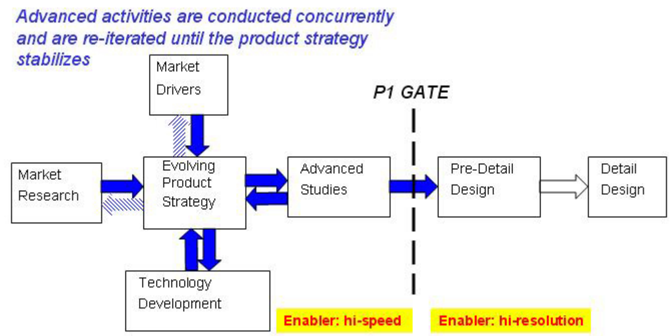

FIGURE 1. From conceptual to detail design acc. to Brophy [2]

Obviously this approach is not applicable in the conceptual design phase as the time needed to iteratively combine the solutions of the various disciplines into a consistent design is much too high. The combination of being able to generate many design solutions in a short period of time inevitably translates into less accuracy of the results. This is also aggravated by the little data available at this early time of development. One approach to satisfy all the constraints is the usage of multidisciplinary engine design systems. These programs consist of two main parts. The physical modules, which include all design algorithms of each of the mentioned disciplines and the control unit, which controls the input and output of the program, the data flow between the physical modules and the numerical solver. Experience shows, that it is already very demanding to be an expert in one of the mentioned areas. Combining the detailed physics of all of these disciplines in one tool would increase the demand to the user extensively. Considering the high amount of design solutions a preliminary design system has to be able to generate in a short period of time, the implementation of high sophisticated expert tools such as 2- or 3-dimensional CFD- or FEM-tools does not seem to be conducive. Therefore simplified design algoritms have to be developed, which are able to generate physically meaningful results in a short period of time. Although these simplifications, the usage of such systems translates into a true challenge as the designer needs to be aware of the design algorithms implemented in the tool. However, one of the big advantages of these programs is, that the interdisciplinary dependancies, which, within the detailed design phase, are accounted for by iterating the process, are automatically considered by the tool.

Multi-Disciplinary Preliminary Design Systems

According to Smith [3] the first preliminary design systems were developed during the 1970's. First computer codes for performance calculation became available. In addition to these the first parametric decks were introduced, which used design point input to calculate weight and external envelope dimensions. Simple empirical algorithms were used to dimension the major modules of the engine. Therefore dimensions from existing designs were scaled based on thermodynamic parameters such as the corrected flow as described by Halliwell [1]. Subsequently the geometric information determined was used to estimate the weight of these modules by applying statistics. During the 1980's the algorithms were refined and models to estimate system level costs were intergrated into the tools. With increasing computational power multidisciplinary preliminary design tools were emerging in the 1980s according to Bretschneider [4]. Tools, which until then were used standalone, were linked together to broaden the perspectives of the conceptual design studies. Additionally this decreased the time to generate feasible design solutions significantly, as the system automatically accounts for input and output operations. More sophisticated design methods were implemented such as weight estimation algorithms based on an aeromechnical design of the various engine modules. In contrast to the empirical methods physically reliable predictions could be made even for designs where no reference was available. The introduction of methods to estimate production cost, maintenance cost and acoustics expanded the fields of application of such systems.

In 1999 Lytle [5], working with NASA, published information about the Numerical Propulsion System Simulation (NPSS). This program aims to enable accurate information about propulsion system parameters such as performance, operability and life to be determined early in the design process before any hardware is built and tested. Therefore NPSS provides modeling techniques and data standards to couple the relevant desciplines such as aerodynamics, structures, heat transfer, combustion, acoustics, controls and materials. The system is developed by NASA, industry, other government agencies and universities and consists of engineering models, a simulation environment and a computing environment. Contradictory to most of the other design systems NPSS is commercially available. According to Lytle [5] a major engine manufacturer estimates, that NPSS has the potential to decrease design and development cost by about 30 to 40 percent through fewer redesigns, re-tests and rebuilds of costly hardware. This translates into savings of $100 million and over a year of development time.

In 2003 Jones [6] published details about the military engine preliminary design process used by Rolls-Royce to support 'capability vs. cost' trades conducted at the weapon system level. In order to accomplish that Rolls Royce makes use of the preliminary multi-disciplinary design system Genesis, which has been developed since the early 1970s. This programme is able to make basic assumptions about key aerodynamic and mechanical parameters to enable the calculations to be started. Genesis uses Rolls Royce Analysis Program (RRAP) to represent the thermodynamic behaviour of the engine. Subsequently the output of the cycle calculation is used as input to build up the geometry of the flow path. This information is then used to mechanically design major parts such as the disks. In order to allow for real features such as bolts, seals and drive arms and correct geometry Genesis makes use of correlations based on a database of Rolls-Royce engines. The mass is defined for the whole engine along with a centre of gravity and also down to a reasonable level detail e.g. blades and discs. The program also has methods to estimate engine unit and development costs. The methods to calculate unit costs are based on key geometric parameters as well as on mass data. Again correlations are applied to account for real features. Genesis provides two methods to estimate development costs. The first uses correlations based on historical development programme costs and the second method is risk based and allows the engineer to decide the level of "right-first-time" that will be achieved.

In 2002 Panchenko [7] from Pratt & Whitney Canada published an introduction to their preliminary multi-disciplinary design optimization tool (PMDO). Besides an aerodynamic calculation providing the geometry of the flow path PMDO is capable of mechanically designing the basic rotating disk geometries. According to Panchenko it was planned to expand the tool to account for additional disciplines such as air-system, dynamics, mass, cost, noise emissions and the generation of the full engine cross section.

In 2010 Brophy [2], also working with Pratt & Whitney Canada, published an introduction another in-house preliminary multi-disciplinary optimization tool (PMDO-Lite). PMDO-Lite is an accelerated but simplified version of PMDO. Similar to Rolls Royce' Genesis PMDO-Lite is based on a thermodynamic cycle calculation, which provides the input to the preliminary sizing tool. This sizing tool is meant to be the core of PMDO-Lite. The gas path as well as key mechanical dimensions, parametric masses and costs are calculated. The major objective of this part of the tool is the quick turn from cycle data into geometry. This was found to be one of the most critical time paths existing in the preliminary design process. In order to achieve that modeling was simplified to the minimum required to obtain a computationally light tool with just enough resolution to allow mechanical designers to get started on a valid basis. Another critical path was found to be the time needed to pre-calibrate the tool prior to use. Semi-automated re-calibration capabilities operating in reverse engineering mode on the basis of feedback data from higher resolution sources and a limiting of the model complexity decreased the time needed to pre-calibrate. The aerodynamic calculation conducted within the sizing tool of PMDO-Lite also provides component efficiencies. Currently there is no automatic adjustment of the estimated cycle efficiency to match the one calculated within the aerodynamic module. This has to be done manually by the user. PMDO-Lite is fitted with a post-processor, which is used to visualize values of about 200 key design parameters. Within this post-processing procedure the model values are compared to values stored in a database. The database consists of reference values from existing certified engines as well as from rig tests, successfull demonstrators or other sources substantiating successful results. Is the model value within a range reference values from existing certified engines exist these are marked green. These, were reference values from rig tests, demonstrators, etc. exist are marked yellow. Values for which no reliable source exist are marked in red. As part of the European research project VITAL (EnVIronmenTALly Friendly Aero Engines) [8] the Techno-Economic and Environmental Risk Assessment tool TERA2020 was developed aiming the development of low pressure spool components considering the ACARE 2020 goals [9]. TERA2020 is build from the following seven modules:

1. Performance calculation using TURBOMATCH [10]
2. Weight and Dimensions
3. Production Cost
4. Aircraft
5. Gaseous emissions
6. Perceived noise
7. Environmental module

The data exchange among the different modules is done using the commercial software iSight [11].

MTU's Preliminary Design System

The development of MTU's preliminary multi-disciplinary engine design tool MOPEDS (Modular Performance and Engine Design System) started in the early 1990s. The main tasks of this tool is to simulate the behaviour of existing engines, e.g. within competitive studies or to conduct parameter studies aiming to find the optimum engine cycle considering all interdisciplinary dependancies. This is typically achieved by calculating the fuel burn (FB). This parameter depends on both thermodynamic parameters and the mass of the engine. That makes it a useful mean to quantify the quality of the engine design. During such studies it is of major importance, that MOPEDS is able to predict the trends of the FB correctly. A high absolute accuracy of the results is of minor importance. The prototype of the tool was described by Schaber [12] in 2000. As the basic technical structure of MOPEDS was already presented by Schaber et al. [13] and Jeschke et al. [14] in 2002 the following chapters will briefly introduce the capabilities of the tool by demonstrating the calculation methods implemented within the various physical modules. The calculation sequence of the tool is depicted in Figure 2. Due to the modularity of the system the possible configurations to be modeled are technically unlimited. Within the following introduction the interdisciplinary dependancies and the way MOPEDS accounts for these are discussed.

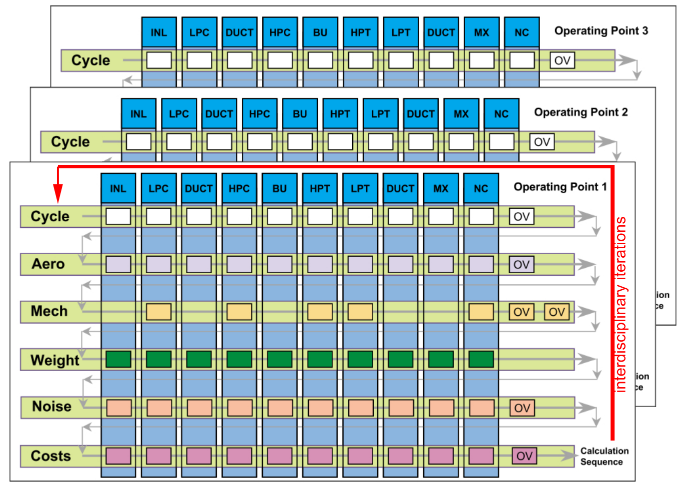

FIGURE 2. Modularity and calculation sequence of MOPEDS acc. to [14]

Thermodynamics

As depicted in Figure 2 MOPEDS is an extension to MTU's performance program MOPS (Modular Performance Synthesis) [15] and therefore shares its program structure. This guarantees a quick and easy data transfer among the various disciplines, which speeds up the calculation time, as many design algorithms within the subsequent disciplines depend on results of the previous calculations. The thermodynamic cycle calculation is the basis of every MOPEDS model, providing parameters such as temperatures, pressures and mass flows. Once the cycle has been selected either the mach numbers or the effective areas at the components' exit as well as the mechanical spool speeds have to be prescribed. Although this input does not effect the cycle design calculation the information is needed to set up the flow path geometry and the design of the turbomachinery within the subsequent disciplines.

Aerodynamics

Main task of the discipline *Aerodynamics* is the generation of the flow path geometry. First the shape of the turbomachinery is generated including the blades and vanes. MOPEDS provides several methods for this task. If no geometrical information is available at all a method can be used, which automatically builds-up the geometry of the turbomachinery flow path and blading. Therefore the method uses knowledge based values stored within MOPEDS for parameters such as stage efficiencies, stage pressure ratios, hub-to-tip ratios, aspect ratios, taper ratios and slope angles. Additionally the thermodynamic properties at the components inlet and exit are provided by the discipline cycle. In case geometric information is available, e.g. from a given module general arrangement, the data can be provided as input. MOPEDS makes use of calculation planes, which are located between the airfoil cascades. Generally there are two different ways the location of these planes can be prescribed. Either in an absolute (fixed plane coordinates) or in a parameterized manner. For the latter one the plane coordinates are calculated using non-dimensional geometrical parameters such as relative areas and hub-to-tip ratios to fix the radial position of the flow path. The effective component inlet and exit areas are provided by the discipline cycle, which ensures consistent area values among the disciplines. In order to account for boundary layers blockage factors can be applied. Aspect ratios as well as row-width ratios are then used to determine the axial coordinates of the calculation planes. Additionally taking the blade taper ratios into account the airfoil geometry is created. In order to support the user to easily and quickly determine the geometrical input a standalone tool can be used, which is capable of the digitalization and the subsequent editing the shape of existing flow paths. The digitalization process follows a specified procedure, which guarantees reproducable results. This procedure accellerates the process of building-up a geometric model in MOPEDS significantly.

Once the flow path geometry of the turbomachinery is generated, the shape of the remaining modules such as the ducts, the combustor and the nozzles can be determined. As these modules are directly connected to the compressors and turbines the inlet and exit coordinates are already fixed. In case of the ducts struts can be modeled to account for geometries such as intermediate casings or turbine center frames. Since the nacelle has huge influences on both the drag and the mass of the propulsion system it has to be accounted for when conducting parameter studies where the geometry of the engine varies significantly. Thus, a standalone tool was developed, which uses thermodynamic parameters as well as the geometry of the flow path to design the nacelle [16]. The nacelle mass is passed on to the discipline weight where it is used to calculate the total weight of the propulsion system. The drag generated by the nacelle is also determined and subsequently used to calculate the installed specific fuel consumption (SFC) and the FB.

The second task of the discipline *Aerodynamics* is the determination of the turbomachinery efficiencies. Therefore standalone aerodynamic meanline and through flow programs are coupled to MOPEDS via interfaces. These expert tools are being developed by the specialist department and are run within MOPEDS in a predefined simplified mode. These simplifications decrease the amount of user input and therefore the demand on the user. Experience has shown, that this approach is applicable for the usage within MOPEDS. Considering the calculation sequence depicted in Figure 2 it becomes obvious, that these efficiencies are already needed within the cycle calculation. In order to avoid discrepancies between the efficiencies used for the thermodynamic calculation and the one determined within the discipline *Aerodynamics* internal multidisciplinary iterations can be enabled to equalize these.

Mechanics

The primary objective within the discipline *Mechanics* is the determination of the component masses, their centers of gravity and the mass moment of inertia of their rotating parts. The latter is especially important to study operability questions of a new concept. Within this discipline all major parts of the turbomachinery are mechanically designed. This includes the airfoils, the attachments of the rotor blades, the disks and the relevant casings. Blades and blade roots are typically assessed by 1D beam theory methods ([17], [18]). The design of casings is done by semi-empiric formulations which allow to fulfill the containment criterion. In order to estimate turbine and compressor disks, 1D finite difference and 2D finite element methods are used to solve the elasticity and heat conduction equations by an inverse method which allows to find the lightest feasible design. Because the simplified design algorithms employ real material data a second objective can be addressed by this discipline. Bretschneider [4] describes, that material data is never non-dimensional. Thus the resulting mechanical design is always dependent on the absolute stress and temperature levels as well as the geometric size. Both is strictly limited and only dependent on the available materials. A design of an engine part is only feasible within the applicability range of its material. Within this context, the results of the conceptual design methods can indicate the limitations of the feasible design space were a valid solution becomes difficult to achieve. If the mass and the mechanical characteristics of the conceptual designs are assessed by the application of knowledge-based design methods instead of mere photo-scaling approaches, a more integrated understanding on the interdependency between cycle parameters, aerodynamic shaping and mechanical limitations and constraints is achieved. This is best explained by a simple example: In order to improve the efficiency of a high pressure turbine for a given expansion ratio and rotational speed, aerodynamics will require the largest possible turbine diameter because this lowers the aerodynamic loading. With this, the larger diameter will decrease flow path height and thus reduce airfoil mass. In contrast, a larger number of airfoils becomes necessary and their more outward position increases the disk rim load again. This requires a stronger disk which in itself already has a larger diameter and thus a larger mass. The turbine diameter itself will also be limited by either the blade root stress or the disk stability. The resulting change of the final component mass is far from trivial and will not be equal to a photo-scaled equivalent. The aerodynamical design space of a turbomachinery and different feasible

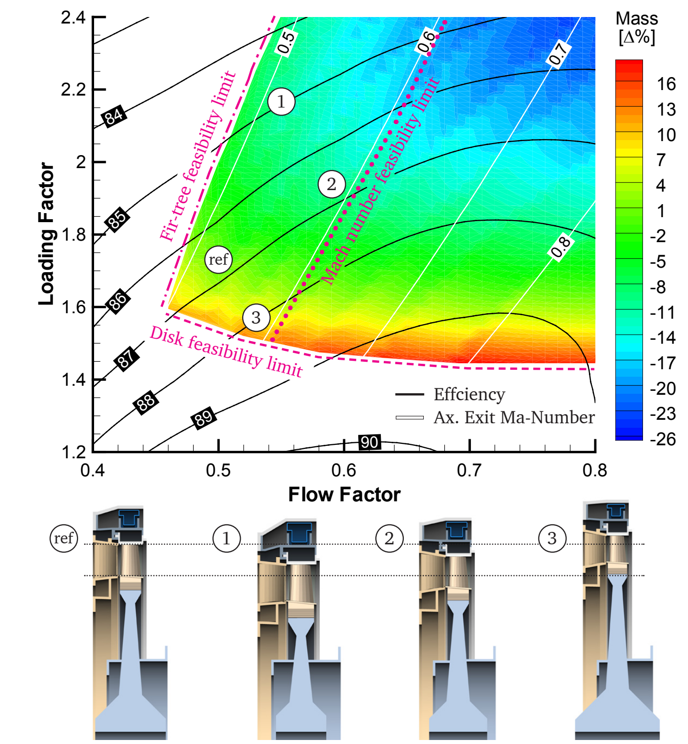

FIGURE 3. Aerodynamical Design Space of a Turbomachinery according to [4]

designs are depicted in Figure 3.

Weight

The overall efficiency is defined as the product of thermal and propulsive efficiency. Looking at the performance of today's engines shows, that the thermal efficiency has already reached a level, where further improvement translates into a very time- and cost-intensive work. Thus, in order to increase the overall efficiency the propulsive efficiency has to be increased. This is achieved by increasing the bypass ratio (BPR), which in turn increases the fan diameter and therefore the nacelle dimensions too. According to Donus [19] the propulsor takes up to 25% of the total engine mass. Considering these dependancies it becomes obvious, that at a certain point the gain in total engine mass balances the increase in propulsive efficiency. From that point increasing the BPR translates into an increase in FB. In order to identify this limit, mass estimation methods are applied already within the conceptual design phase. There are two main fundamentally different types of mass estimation methods: the first uses pure statistics based on key geometric and thermodynamic characteristics, the second involves more detailed modeling of the various engine hardware elements. The best estimation method strongly depends on the actual task. In case derivatives of a basic engine have to be designed, e.g. to establish family concepts, statistical methods can be advantageous, as the basic configuration and the technology level is typically very similar. However, to achieve high mass estimation accuracies a good database is one of the basic requirements. MOPEDS provides several statistical methods to estimate the mass of the various components as well as the overall engine. These are based on the geometry as well as on key thermodynamic parameters.
The natural advantage of the second type is, that reliable weight estimations can even be obtained when unusual or even brand new engine concepts are investigated, were the pure statistical methods mentioned tend to fail. As mentioned in the previous section the one implemented in MOPEDS is based on the mechanical design of the various parts. The material density and the volume provided by the discipline *Mechanics* are used to calculate the mass. The material density is taken from the official MTU material database, which is linked to MOPEDS. Currently this method covers the following parts:

- Turbomachinery including
  - Disks
  - Wings
  - Airfoils
  - Casing
- Ducts including
  - Struts
  - Casing
- Nacelle

A detailed description of this method and the accuracy level, which can be achieved was reported in 2009 by Donus [19]. Once the geometry and the weight of the various parts are determined these data can be used to calculate the center of gravity (CG) of the engine. This information is of special interest for the aircraft manufacturer as it is required for the aircraft weight and balance calculation.

Acoustics

In addition to economic considerations, environmental factors are becoming more and more important in the development of new engines. The requirements such as those defined by ACARE [9] have a significant impact on future engine development. For this reason parameters such as noise emissions are already taken into account within the conceptual design phase. This is particularly important when observing unducted concepts such as open rotors.
Within the discipline Acoustics of MOPEDS noise emissions of the various engine components as well as airframe induced emissions are assessed. Same as in the disciplines described before standalone tools, which were developed within the specialist departments are linked to MOPEDS. In order to limit the demand

on the user several input parameters are automatically set to defaults by the interface.
The fan module determines the noise due to the aerodynamical interaction between rotor and stator and inlet distorsion as well as broad band noise and buzz saw noise. The algorithms are based on results of the aerodynamic and thermodynamic calculations. The noise generated by the interaction between fan and low pressure compressor is also considered. The turbine and combustor modules contain far-field noise calculations. The results of these calculations are provided as a function of the angle. Inputs are the relevant geometric and aerodynamic data. As mentioned before MOPEDS is also capable to estimate the noise emissions induced by the airframe. In particular this is the noise generated at the leading and trailing edge of the wing as well as the noise emitted by the extended gear.

Costs

This discipline contains algoritms for the estimation of the production costs. Similar to the discipline weight there are two fundamentally different types of cost estimation algorithms implemented in MOPEDS. The first one is a semi-empirical approach, which calculates the production costs as a function of a surrogate volume. The determination of this volume is based on the dimensions of the considered component. Subsequently corrections can be applied to the base value to e.g. account for cooled turbine stages, blisks within the compressors or inflation. To quantify the influence of the change in value, the determination of the inflation correction is based on the input of the price basis.
The second method incorporates more detailed modeling based on geometry, material and production parameters. The implemented cost estimation algorithms are detailed described by Schmitz [20] and Riedmüller [21].

Necessity for Calibration

Aero engines in service are the result of a highly complex engineering process that was performed to optimize the final product in every thinkable manner. For this reason the simplified and generalized design laws which are used in conceptual design studies can never fully reproduce the complexity and maturity of a detailed design. They are understood as surrogate models which are expected to represent all governing interrelationships and the underlying physical dependencies sufficiently enough in order to allow a reasonable conceptual design and the generation of derivatives by scaling. Therefore, all design laws require calibration. The major calibration of a method is typically included in form of empirical corrections, which were implemented at the time the design law was created. However, if an existing design is to be remodeled another adjustment becomes necessary so that the outcome of the conceptual design laws is equal to the known original. With this procedure the systematic internal error

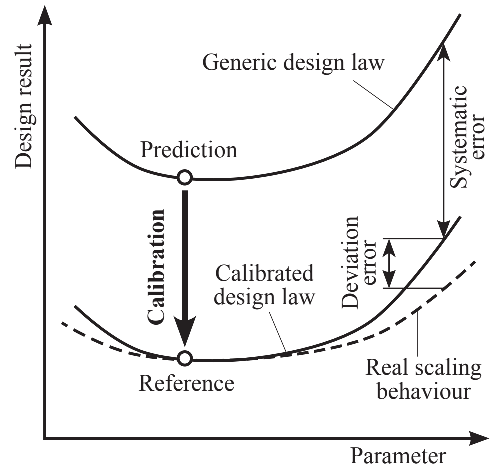

FIGURE 4. Necessity for calibration in preliminary design [4]

of a design law is adjusted to the individual and design-specific particulars and the generic law can now reproduce the known result with a remaining statistical uncertainty. After calibration it is possible to scale a reference design based on the knowledge which is included in the applied design laws. Due to the simplifications the scaled solution will deviate the more from the real design the bigger the distance gets to the reference point (deviation error). The interrelationship is graphically shown in Fig. (4). In general, calibration must be carefully implemented. All corrections must fully influence all succeeding calculations which depend on the calibrated parameter as one of their inputs. The ideal design rule, of course, would have a calibration factor of unity or a deviation constant of zero. But because this is never the case the deviation from unity/zero indicates the quality of the implemented design law. Any improvement of a design law is thus directly connected with calibration constants closer to unity or zero. It is further important to understand that any error which is introduced by the input to a design law is automatically merged into the necessary result calibration constants. It is thus necessary to calibrate design laws in the same sequence as they are applied later. If sufficient enough calibration data is available, it is recommended to calibrate a design law with more than only one reference design. Furthermore, the interchangeability of calibration constants is of special value. Any calibration known from an existing component can be transfered to an unknown design if the technology level of both applications is comparable.

Multi-disciplinary engine design study

In order to demonstrate the application of preliminary design systems a parameter study was conducted with MOPEDS, which aims to find the optimum engine cycle taking into account interdisciplinary dependancies. Therefore several different engine designs were generated and subsequently compared. A two spool turbofan engine model was set up as described in the previous chapters and used as basis for the study. Besides the thermodynamic cycle the geometry of the flow path, the disks and the casings as well as the mass calibration factors of the various modules and parts were adjusted using the re-engineering mode of MOPEDS to match the reference. The geometrical result of this reference engine is depicted in Figure 5. In order to optimize the overall system the BPR is varied from 7.5 to 10 in steps of 0.5. For a fair comparison among the resulting designs the thrust which is needed to power the aircraft is kept constant. This results in a change in geometry not only of the engine but of the nacelle too.

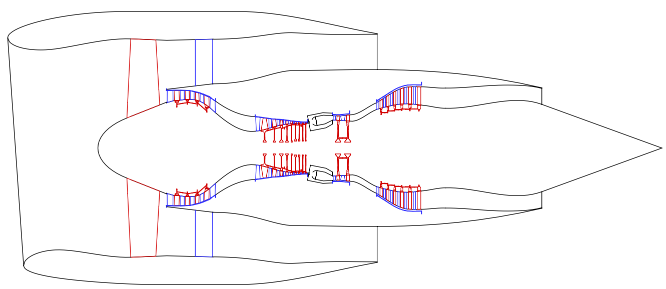

FIGURE 5. General Arrangement of the Reference Engine

These are the boundary conditions of the study:

- Constant installed thrust: $FN + FD - FD_{ref} = const.$
- Constant turbine inlet temperature: $T4 = const.$
- Constant overall pressure ratio: $OPR = const.$
- Constant component inlet and exit Mach numbers
- Total cooling air adjusted according to temperature levels
- Optimum fan pressure ratio for given BPR selected
- Turbomachinery efficiencies reflect aerodynamic loading

Results and Discussion

The results of the pure cycle study neglecting all interdisciplinary dependancies is depicted in Figure 6, where the SFC is plotted against the BPR.

As expected SFC decreases continuously with lower specific thrust, as the propulsive efficiency of the engine is increasing. The optimum for this study is somewhere beyond BPR 10. However, taking into account the various other design disciplines the design optimum will change. With decreasing speficic thrust and increasing BPR the fan diameter increases as well. Assuming a constant fan aerodynamic loading $\frac{\Delta h}{u^2}$ in order to maintain a constant technology level low spool speed decreases with increasing fan diameter. Without any countermeasures the aerodynamic loading of the low pressure turbine (LPT) would increase and consequently the LPT efficiency would decrease. Considering that the LPT efficiency has a strong influence on SFC in this study the radial position of the LPT was reasonably adjusted. Within this study this is achieved by adjusting the LPT inlet hub to tip ratio so that the aerodynamic loading is kept constant; the LPT moves outwards. The changes in geometry for the designs of BPR 8, 9 and 10 are depicted in Figure 7. For this study that means that with higher BPR's the LPT ν increases, too. Obviously the change in radial position has an influence on the mass

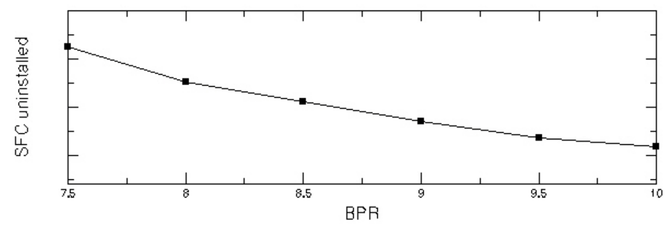

FIGURE 6. Specific Fuel Consumption vs. BPR

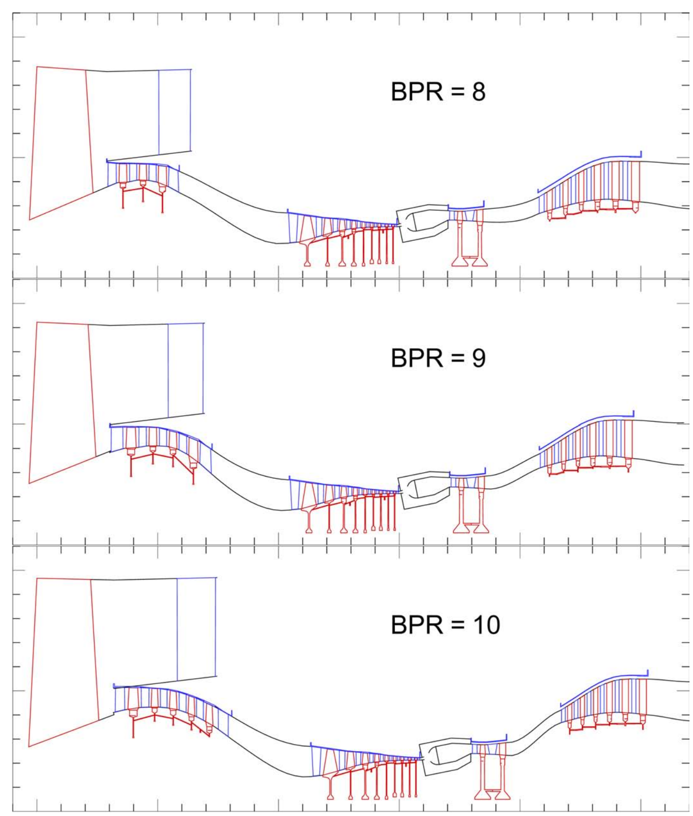

FIGURE 7. General Arrangements for BPR 8, 9 and 10

of the component. Moving the LPT outwards increases the number of airfoils assuming constant pitch to chord ratio. The flow path height however decreases, as the Mach number at the LPT inlet is constant and the LPT ν increases. The results show that from BPR 7.5 to BPR 10 the blade number increase amounts to 36% while the total blade mass is dropping by 2% as the flow path height decreases. The combination of decreasing low spool speed and lower blade mass has two beneficial effects. First, the rim load, which has to be sustained by the disk, decreases and second the kinetic energy of the blade, which has to be absorbed by the casing in case of a blade off scenario, decreases as well. However, due to the higher mean component diameter for high BPR designs the component mass increases by 25% between BPR 7.5 and 10. The booster is also effected by the low spool speed change. As well as for the LPT the aerodynamic loading of the booster increases with higher BPRs. Therefore the booster stage numbers are adjusted so that the aerodynamic loading is within a reasonable range. The variation of the module mass fractions for three different BPR's are depicted in Figure 8. Looking at these fractions it can be seen, that due to the higher

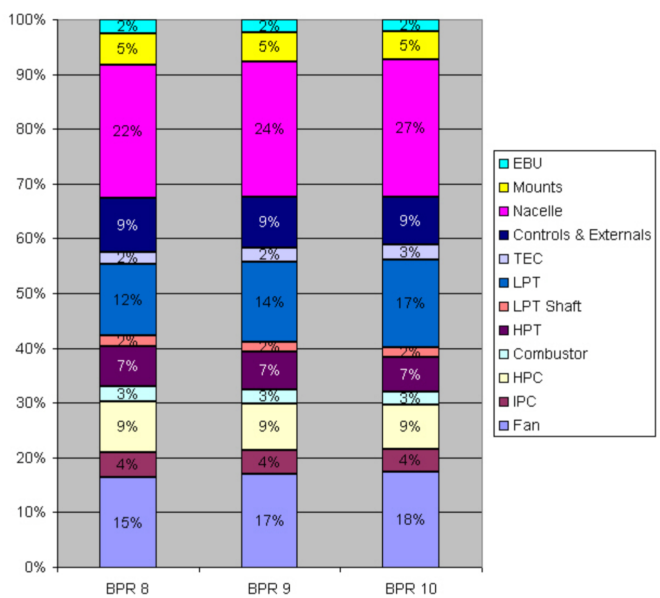

FIGURE 8. Component Mass fractions on Total Engine Mass

fan diameter with increasing BPR, the sum of the fan, the LPT and the nacelle amounts to 62% of the total engine mass for BPR 10 compared to 49% for BPR 8. In order to quantify the impact of the change in SFC, mass and drag on the total aircraft system trade factors are applied. These factors are the result of aircraft simulations taking into account the flight mission and the configuration. The effect on the mission fuel burn is depicted in Figure 9 based on the reference engine model. The change in total propulsion system (PPS) mass is depicted in Figure 10 based on the PPS mass of the BPR 7.5 design. A clearly visible shift of the optimum engine cycle towards lower BPRs can be observed. This study showed, that although only the low pressure system was varied the demand on the user is quickly increasing while considering the effects of the various disciplines on the engine design.

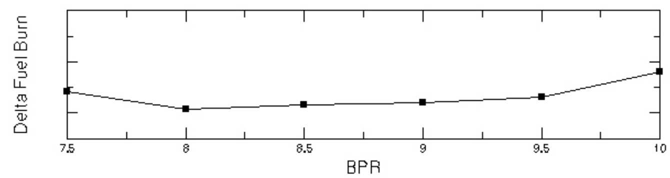

FIGURE 9. Delta Fuel Burn vs. BPR

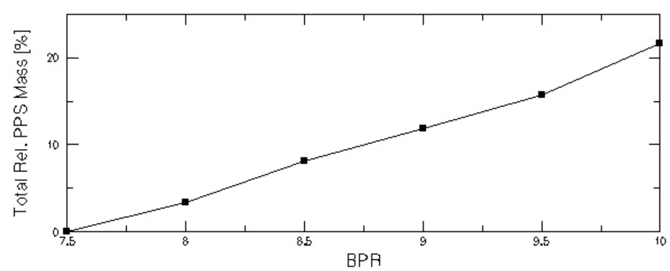

FIGURE 10. Relative Propulsion System Mass vs. BPR

Conclusion

In todays working environment project engineers have to deliver reliable data in a very short time period to allow the upper management to decide over the participation in new engine programs. The quality of the data has to be such that key propulsion system parameters (SFC, PPS mass, etc.) show the right order of magnitude. To accomplish such a task is only possible by application of sophisticated expert systems. This paper shows the application of such a tool, in this case represented by the MTU's inhouse code MOPEDS. Unlike the traditional way here different aspects of whole propulsion systems like thermodynamics, aerodynamics, mass assessment, etc. are calculated at the same time and in a consistent to way. This procedure only takes seconds instead of weeks in earlier times. It was shown that the combination of interdisciplinary aspects lead to a multidimensional solution space that cannot be handled anymore by rules of

thumb. However, the complexity of expert systems like the described one demand a sophisticated compilation of functionalities, (e.g. an annulus editor, an online-help, adequate diagnostics tools, plot catalogues etc.) in order to avoid an excessive demand on the user.
With MOPEDS MTU Aero Engines has developed an expert system with which a reasonable compromise between performance and user knowhow could be achieved.

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