Performance Modelling of an Ultra-High Bypass Ratio Geared Turbofan

A. Alexiou, N. Aretakis, I. Roumeliotis, I. Kolias and K. Mathioudakis

LABORATORY OF THERMAL TURBOMACHINES
National Technical University of Athens, Greece

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DEMOS

Developing advanced Engine Multi-disciplinary Optimization Simulations

DEMOS Partners

Topic Manager

Project Consortium

NTUA

DEMOS Objective

The project DEMOS objective is to develop a flexible and extensible modular multi-disciplinary **framework** and undertake design space exploration and multidisciplinary optimisation assessments of novel Ultra-High Bypass Ratio (UHBR) and open rotor propulsion concepts at aircraft mission level.

The framework will comprise two main elements, PRopulsion Object Oriented SImulation Software (PROOSIS) and a customised Techno-economic Environmental Risk Assessment Framework (TERA2050).

Scope of Paper

In the context of the DEMOS project, the present study demonstrates a **methodology** for integrating at the same modelling level and within the same simulation environment engine thermodynamic performance, turbomachinery component aerodynamics, flow path generation and weight estimation, all within a multi-point design calculation that considers simultaneously a set of discrete operating points in the engine flight envelope.

Next, the setting up of an Ultra-High Bypass Ratio (UHBR) Geared Turbofan (GTF) engine performance **model** with Variable Pitch Fan (VPF) and/or bypass Variable Area Nozzle (VAN) is described. Multi-parametric studies are then carried out to generate a design space of engine cycles according to specified targets and limits.

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- Installed Performance
- Integrated Multi-Point Design Approach

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- The UHBR GTF Model Setup
- Model Results
- Parametric Studies

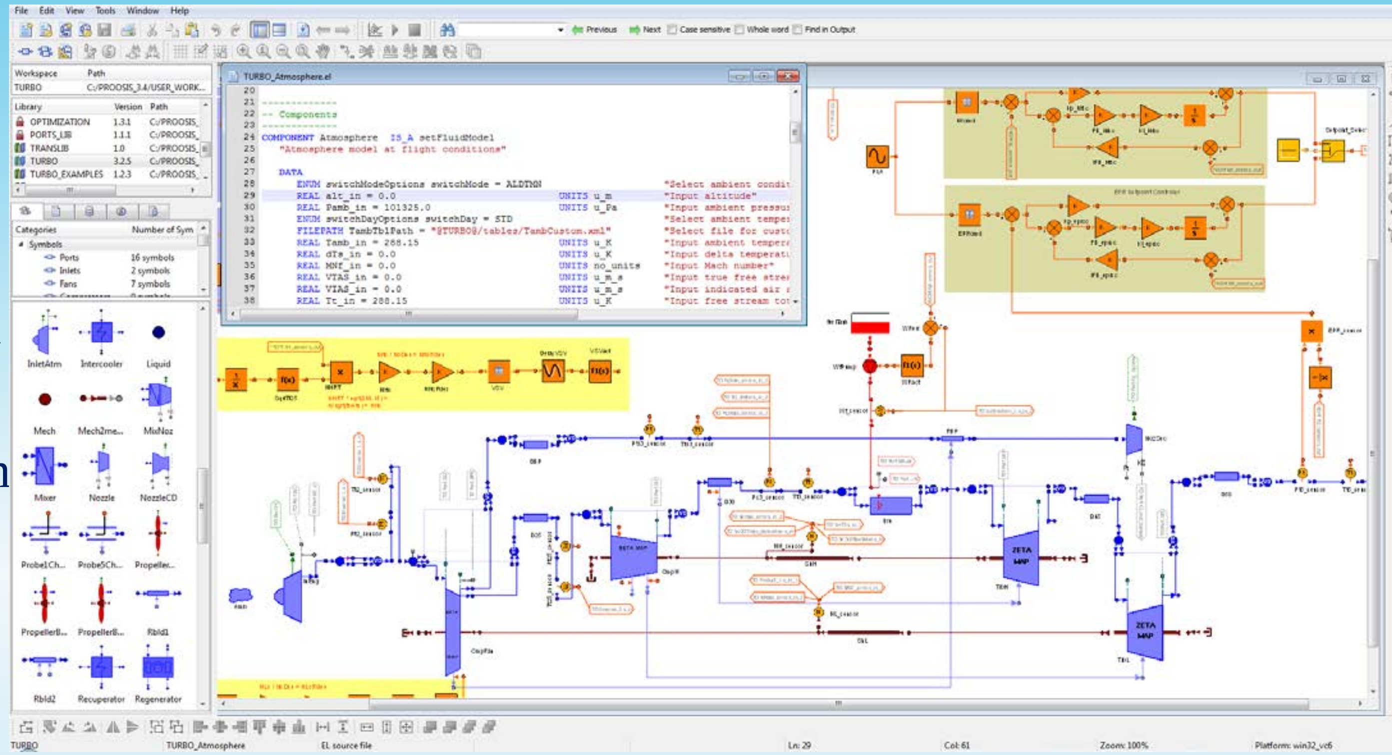
❑ Summary & Conclusion

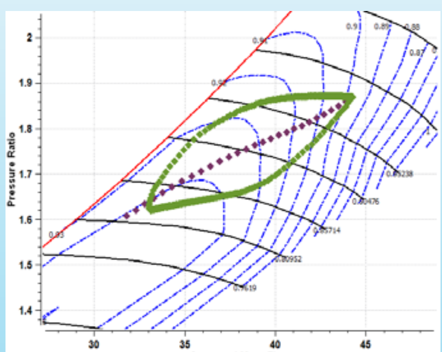
Methodology: Framework Requirements

- Modular approach comprising robust, accurate and fast execution models
- Any gas turbine configuration
- Any engineering discipline
- Any level of fidelity
- Any calculation type
- Results visualization
- Quick model setup time through user-friendly interface
- Connectivity with other engineering software applications

Simulation Framework: PROOSIS Platform

- ➢ Object-Oriented
- ➢Advanced GUI
- ➢ Steady State
- ➢ Transient
- ➢ Mixed-Fidelity
- ➢ Multi-Disciplinary
- ➢ Distributed
- ➢ Multi-point Design
- ➢ Off-Design
- ➢ Test Analysis
- ➢ Diagnostics
- ➢ Sensitivity
- ➢ Optimisation
- ➢ Deck Generation
- ➢ Connection with Excel & Matlab
- ➢ Integration of FORTRAN, C, C++
- ➢ Version Control





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#ESI	--	--	0
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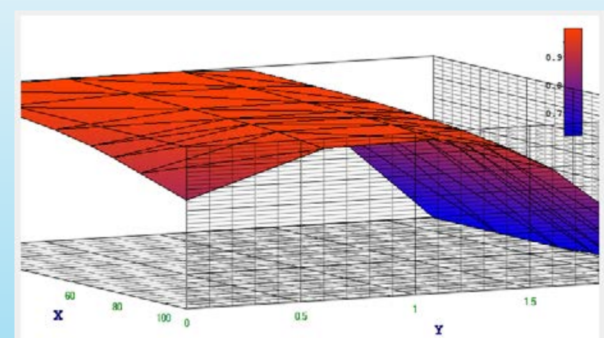
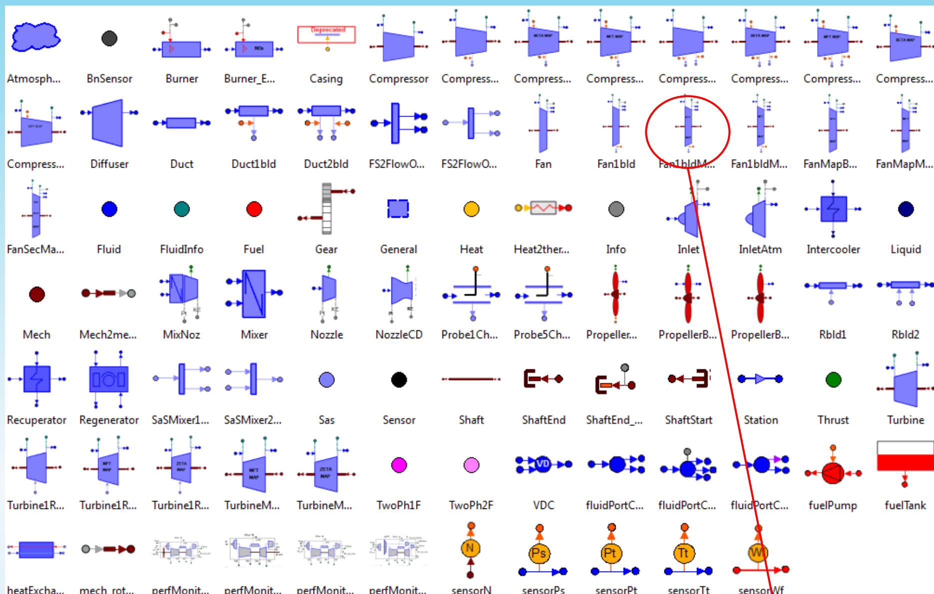
Amb.dTamb (K)	dTamb	--	0
CmpH.BETA (-)	--	--	0.5
NH (rpm)	--	--	9607.23139
TURBO.MNf (-)	XM	--	0.8
TrbH.ZETA (-)	--	--	0.516350527
W1 (kg/s)	--	--	100
SFC (g/(kN·s))	--	--	27
Tt41 (K)	--	--	1301.13095



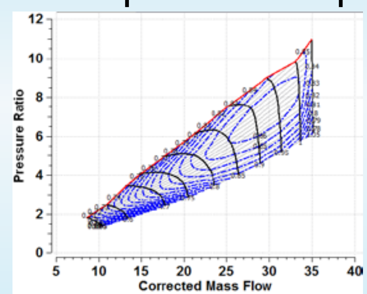
Simulation Framework: PROOSIS Platform

TURBO library of gas turbine components

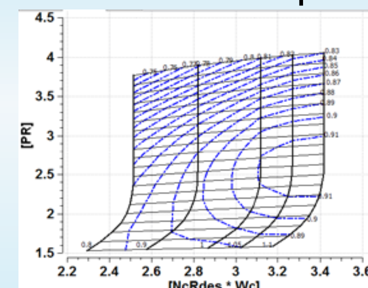


- ❑ **Industry-accepted** performance modelling techniques
- ❑ Respects international **standards** in nomenclature, interface & OO programming

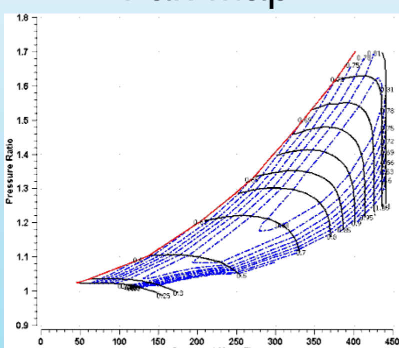
Compressor map

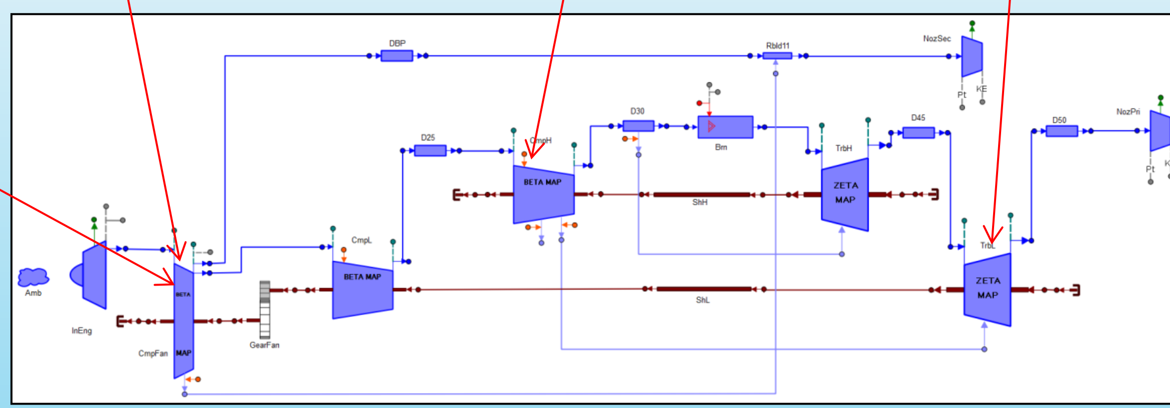


Turbine map



Fan map





Performance Modelling: Variable Geometry

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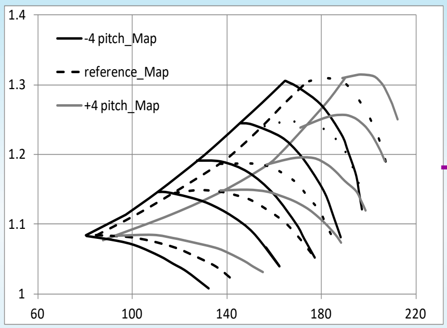
ABSFanMapBETA (TURBO)

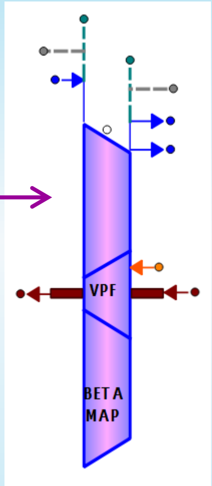
ABSFanBasicMap (TURBO)

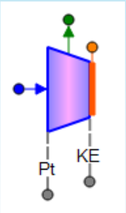
Nozzle (TURBO)

VPfanMapBETA

VANozzle







Variable Pitch Fan (VPF) Component

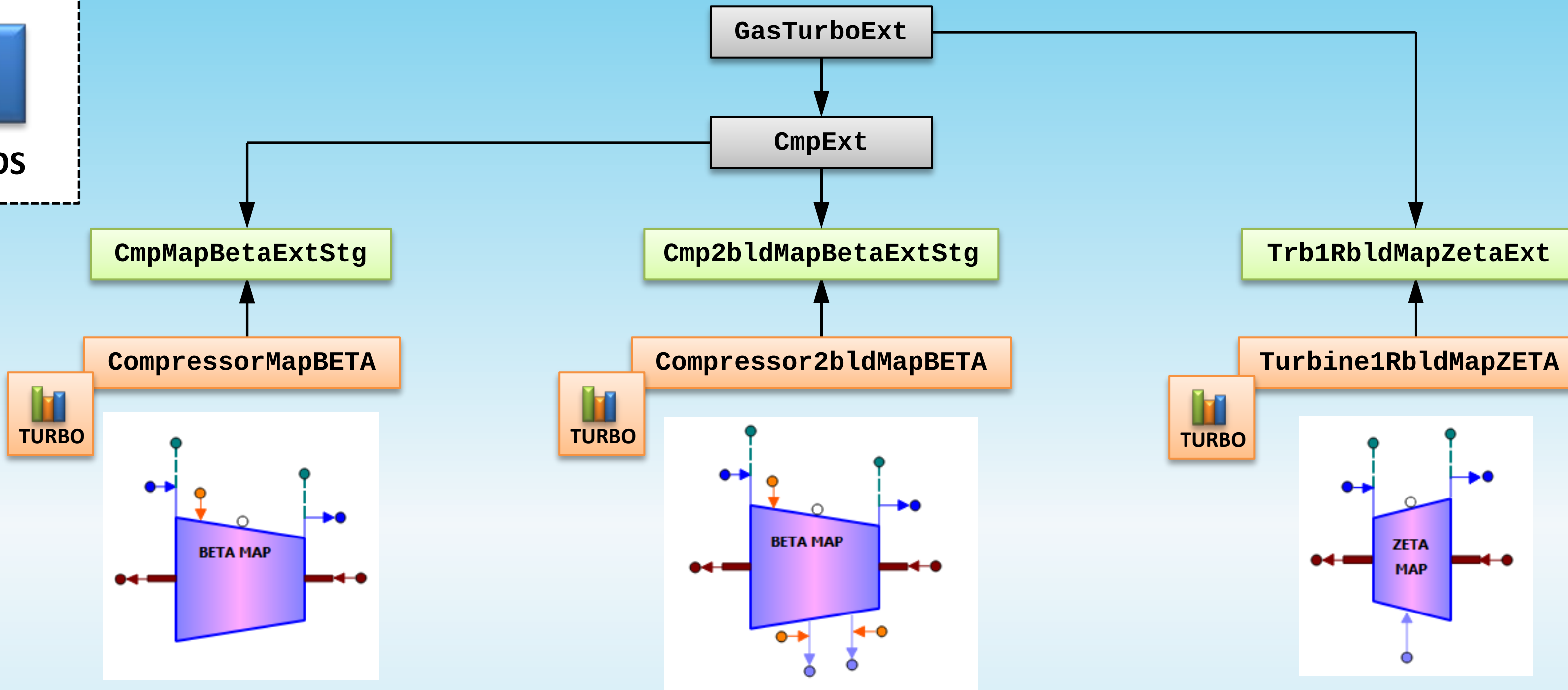
- Change in blade pitch Δβ is an input through control signal port
- Effect of blade pitch change on fan performance (core and bypass) is accounted through 3D maps with Δβ as additional independent parameter
- Design adiabatic efficiency in terms of FPR

Variable Area Nozzle (VAN) Component

- Change in nozzle area ΔA is an input through control signal port
- Effect of VAN on engine performance established through ΔA
- No change in nozzle coefficients due to area change

Turbomachinery Aerodynamic Calculations

DEMOS



Compressor & Turbine Components

- Fully coupled with performance calculations
- Stage-by-stage meanline design (free vortex for tip/hub)
- Aerothermodynamic calculations accounting for bleeds/returns
- Stage and overall efficiencies calculation employing either loss or semi-empirical correlations

Turbine Cooling

Integrated turbine design calculation with row-by-row cooling capability:

- Implemented cooling model* for each row (stator or rotor) including combustor patter factor
- Mixing of cooling flows with turbine flows at each row
- Relative inlet gas temperatures for rotors are used based on velocity triangle calculations
- Cooling air pre-swirl temperature drop is accounted through a swirling factor
- Working potential of cooling flows is calculated according to where they are introduced in the turbine
- Stage efficiency correction for cooling based on cooling mass flow fraction (different for rotors and stators)

* Wilcock, R.C., Young, J.B. and Horlock, J.H., 2005, "The Effect of Turbine Blade Cooling on the Cycle Efficiency of Gas Turbine Power Cycles", J. Eng. For Gas Turbines and Power, 127, pp. 109-120.

Flow Path & Weight Estimation

- The compressor or turbine total **flowpath** geometry is produced from the stagewise flow-annulus dimensions assuming the blade aspect ratio and axial gap distributions
- The lengths of interconnecting **ducts** and burner are established through a specified length-to-radial height ratio. The wall contours are approximated using linear or cubic interpolation between inlet and outlet.
- The **weights** of fan, fan duct, compressors, combustor, turbines, structural supports and control/accessories are estimated using simplified equations from correlations of lift and cruise data of VTOL aircraft (NASA-TM-X-2406).
- The **gearbox** weight is estimated using an empirical correlation expressing gearbox weight as a function of gear ratio and maximum delivered output power (NASA/TM-2012-217710).
- The weight of the **Pitch Change Mechanism** (PCM) of a VPF is expressed as a fraction of the total fan weight.
- The **fan nozzle area** changing mechanism's additional weight is assumed to be only a small portion of the engine's total weight.
- **Nacelle** weight is calculated from a simplified correlation where nacelle elements are represented by approximate cylinders (Jackson, 2009)

Installed Performance

Installation effects are taken into account in this study using a simplified approach*:

- nacelle drag is expressed in terms of specific thrust sFN, flight velocity Vf and an empirical constant k
- the effect of total engine weight Wt_{eng} is assumed to contribute to overall aircraft drag taking into account a specified value of aircraft lift-drag ratio LqD

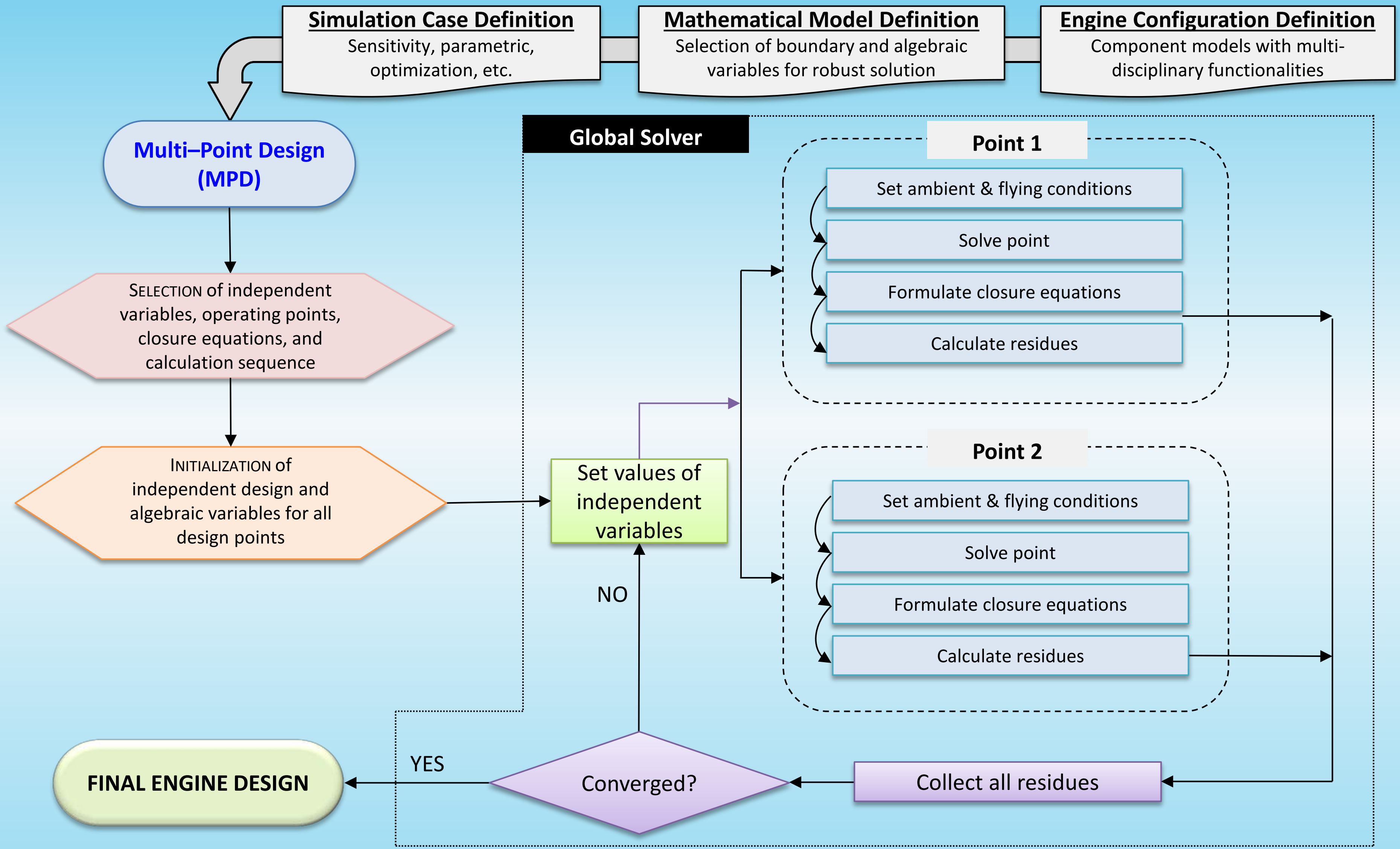
Hence, a corrected net thrust FN_{cor} value can be obtained from the following equation :

$$FN_{cor} = FN \cdot \left(1 - k \cdot \frac{V_f}{sFN}\right) - Wt_{eng}/(LqD)$$

The installed SFC is then simply WF/FN_{cor} where WF is the actual fuel flow rate.

*CUMPSTY, N. and HEYES, A., 2015, “Jet Propulsion: A Simple Guide to the Aerodynamics and Thermodynamic Design and Performance of Jet Engines”, 3rd Edition, Cambridge University Press, New York, USA.

Integrated Multi-Point Design Procedure



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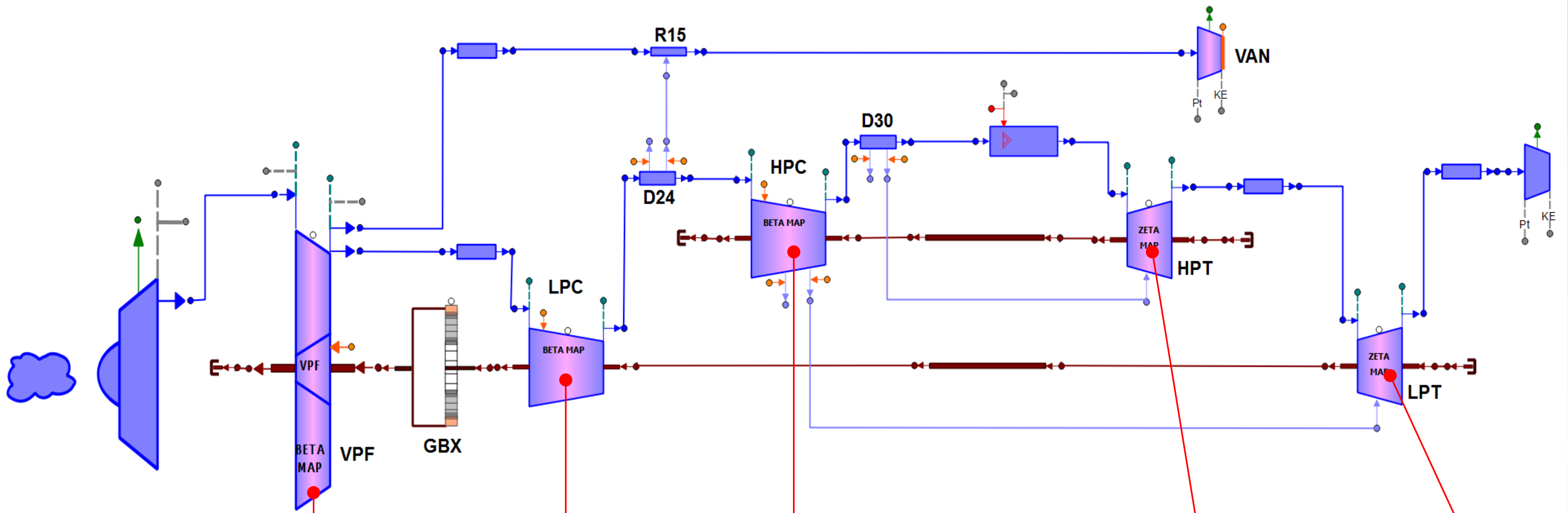
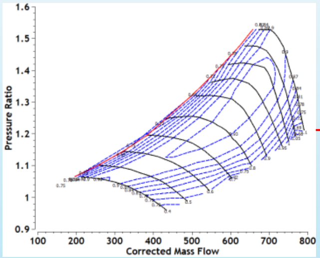
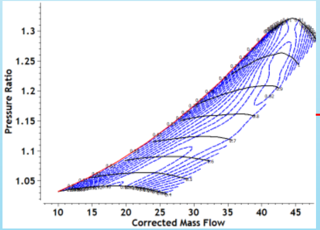
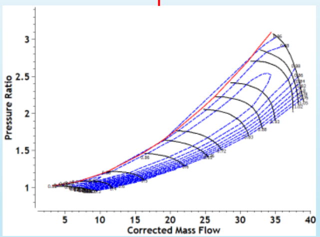
- **Summary & Conclusion**

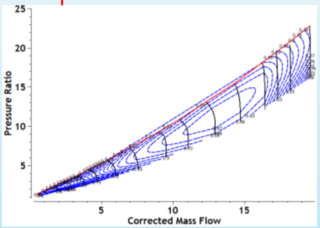
UHBR Engine Model Setup - I

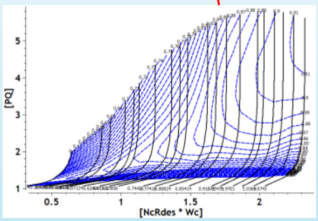


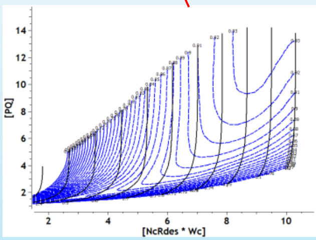












For Δβ = -4°, 0°, +4°

Default Mathematical Model

3700 equations + 951 input data

2 boundary variables (FAR4 & VAN/VPF)

8 algebraic variables (W1, BPR, BETA/ZETA)

2 dynamic variables (shaft rotational speeds)

10×10 Jacobian matrix

UHBR Engine Model Setup - II

Consider an MPD structure with **three** operating points: take-off (TO), top-of-climb (ToC) and cruise (CR).

Extended mathematical model additional independent variables (total of 78):

- the scaling factors of all the turbomachinery component maps
- the HPT cooling flow fractions per stage row
- the inlet and outlet component cross-sectional flow areas
- the gearbox rotational speed ratio
- FAR4 (to match required net thrust at each operating point)
- Variable geometry (VAN or VPF) control signal (to match operability or performance target at TO)

This creates the need for a total of 78 **closure equations** in addition to the model 30 internal closure equations (3 points · 10 algebraic variables). This means that 108 residues have to be evaluated.

UHBR Engine Model Setup - III

Closure equations for establishing design variables:

- the **location** of the design (or reference) point on the maps is specified at ToC through setting the values of the map auxiliary parameters (BETA/ZETA) and corrected speed relative to design.
- Efficiency scaling factors are established by **equating** at CR conditions the cycle variables for fan/compressor polytropic efficiencies and turbine isentropic efficiencies to the corresponding ones in the aerodynamic design calculations.
- **Mach number** values at inlet and outlet of components are specified at ToC to establish the corresponding cross-sectional areas.
- **Metal temperatures** for each HPT row are given at TO.
- Two sets of **inequalities** at TO (one for the LP and one for the HP spool) grouping the turbine blade stress parameter AN^2 (main equality) with upper bounding inequality constraints related to compressor first stage relative tip Mach number at ToC, compressor first and last stage tip blade speed and last stage compressor and turbine rim speed. For the LP spool, an additional inequality is the maximum value of gearbox gear ratio.
- Design values for duct and burner pressure drop fractions and burner efficiency are specified at ToC.

UHBR Engine Model Setup - IV

- The remaining closure equations include specifying at ToC the values of:
  - OPR
  - FPR
  - pressure ratio split between the LP and HP compressors
  - fan corrected tip speed

- OPR is part of an **inequality** group that also includes the compressor exit temperature at TO and the compressor last stage blade height (LSBH) upper bounding inequalities.

- The final closure equation is the value for the **nozzle ideal velocity ratio** at CR. For this parameter, an **optimization** is performed within the MPD process so that the minimum value of uninstalled cruise **SFC** is obtained every time.

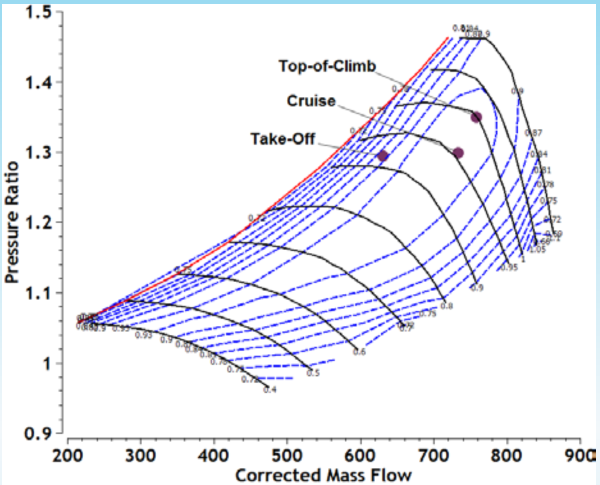
- No constraint has been placed on the maximum fan diameter.

UHBR Engine Model Setup - V

- Fixed turbomachinery **stage** numbers: 1_G_3_8_2_3
- LP and HP **compressors** are designed with the constant mean diameter option and assuming constant stage loading for the LPC and an enthalpy change distribution for the HPC.
- For the **turbines**, linear distribution of mean diameter is assumed with constant loading and symmetrical velocity diagram.
- For the HPT **cooling** model, the values corresponding to the advanced set of cooling technology factors are considered with the exception of the second stage rotor for which no film cooling is assumed. The combustion pattern factors are set to 0.1 and 0.05 for the first stage stator and rotor respectively and 0 for the second stage. No reduction to cooling air temperature due to pre-swirling is considered. The stage efficiency cooling correction factors are set to 0.1 and 0.2 for the stators and rotors respectively.

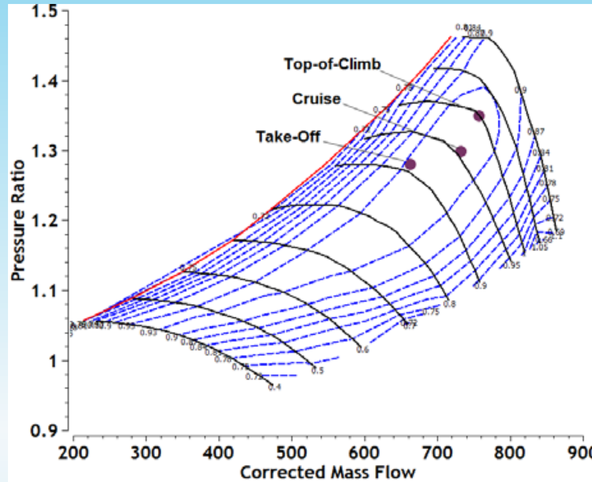
Model Results: Variable Geometry Effects

Location of operating points (CR, ToC, TO) on fan bypass map



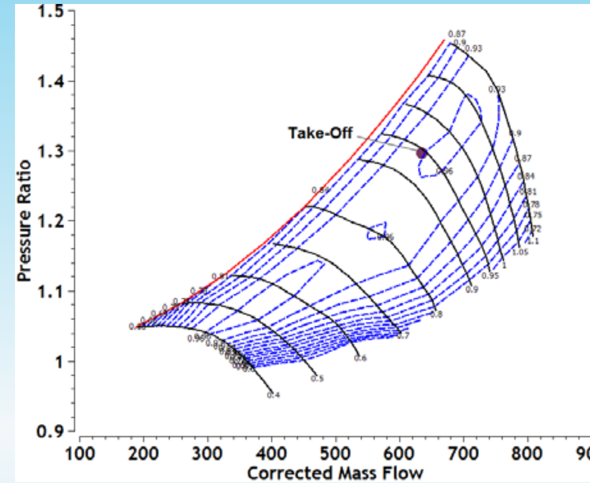
(a)

no variable geometry employed



(b)

VAN opens by 7.7% at TO



(c)

Closing VPF by 4° at TO

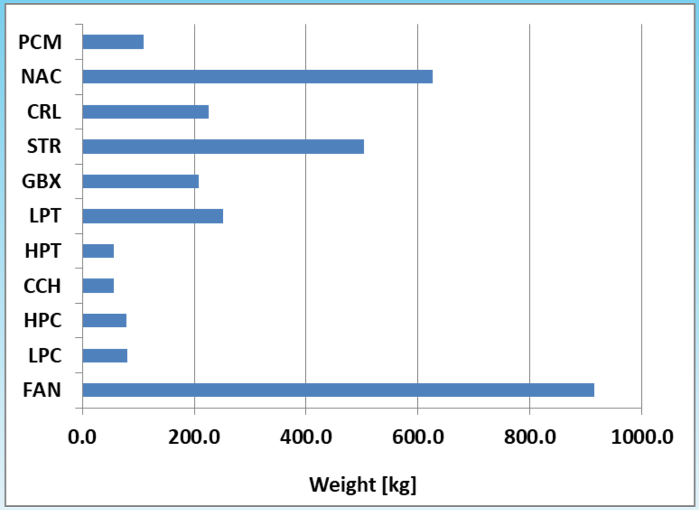
change in variable geometry (nozzle area or pitch angle) is determined from a fixed fan surge margin requirement

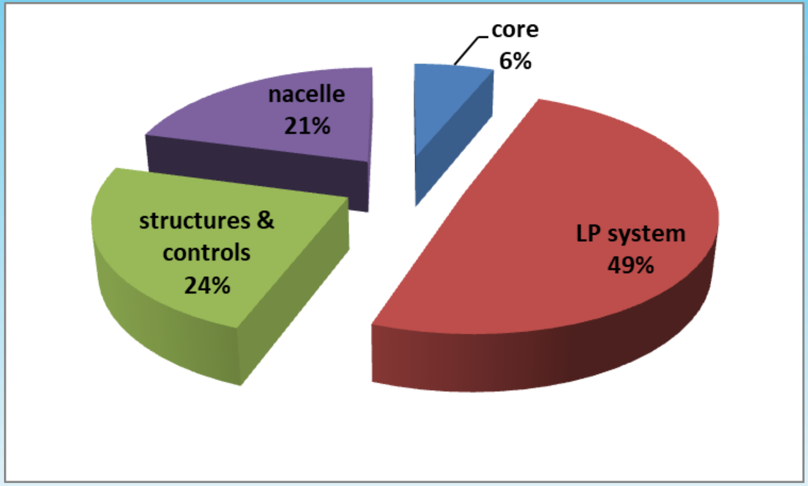
FPR=1.35 (@ToC)
OPR=50 (@ ToC)
COT=1850K (@TO)

Model Results: VPF with $\Delta\beta$ = -4° at TO

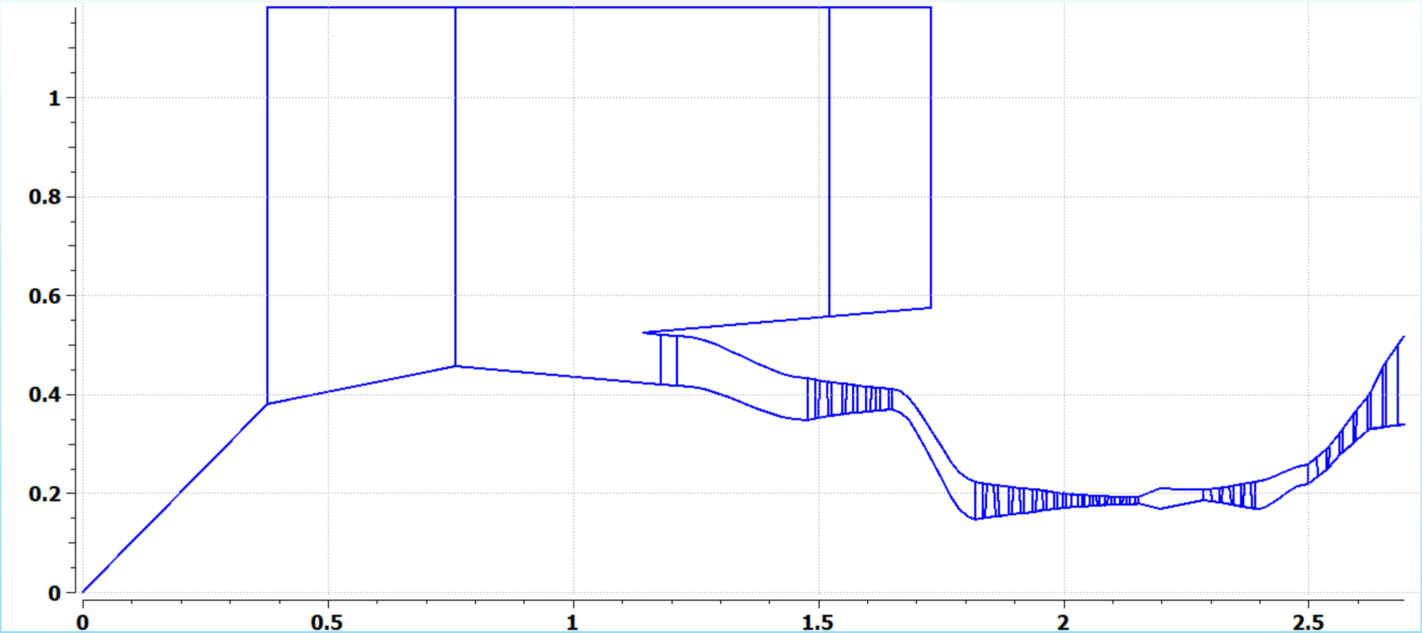
Parameter	CR	TO	ToC	Parameter	CR	TO	ToC
Fan effPoly	0.955	0.960	0.959	Gear ratio		3.5	
LPC effPoly	0.913	0.910	0.906	NH (rpm)	19419	21567	20231
HPC effPoly	0.908	0.909	0.905	NLG (rpm)	2174	2413	2326
HPT eff	0.906	0.908	0.906	Tt3 (K)	780.8	947.4	845.9
LPT eff	0.921	0.915	0.922	Tt4 (K)	1576.4	1850.0	1731.9
FPR	1.299	1.296	1.35	Tt41 (K)	1532.3	1800.4	1683.2
LPC PR	2.52	2.53	2.64	Tt45 (K)	1127.0	1337.7	1245.8
HPR PR	14.7	14.1	15.6	Wcool/W3		9.84%	
HPT PR	4.21	4.19	4.20	HPT Work Potential		0.51	
LPT PR	9.35	7.75	9.63	HPT Tm S1 (K)	1134.9	1350.0	1240.8
OPR	44.2	42.2	50.0	HPT Tm R1 (K)	1047.2	1250.0	1144.4
BPR	19.64	17.97	18.51	HPT Tm S2 (K)	1136.1	1350.0	1246.4
W1 (kg/s)	286.4	678.3	290.7	HPT Tm R2 (K)	1046.5	1250.0	1149.2
VQid	0.75	0.69	0.68	Core Efficiency	0.549	0.506	0.560
Fan Dtip (m)		2.36		Propulsive Efficiency	0.814	0.529	0.791
Fan Ws (kg/(s·m^2))	195.7	170.3	203.1	Transfer Efficiency	0.829	0.833	0.849
HPC LSBH (mm)		13.16		SFC (g/(kN·s))	13.919	9.072	14.018
HPC Ws (kg/(s·m^2))	164.3	155.9	171.2	SFCinst (g/(kN·s))	16.554	9.375	16.203

Model Results: VPF with $\Delta\beta = -4°$ at TO





Weight Distribution



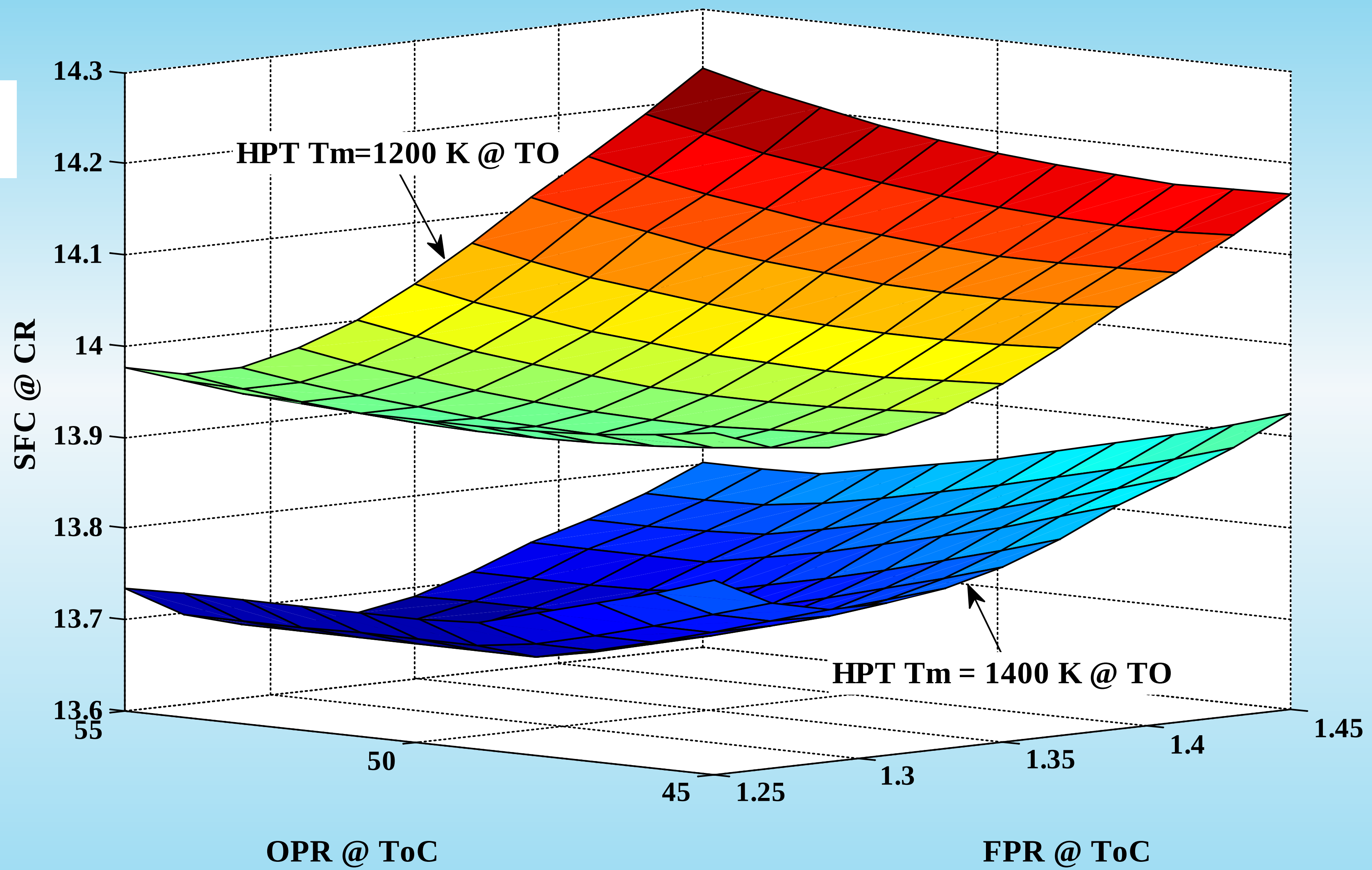
Engine Flow Path

Parametric Analysis: Uninstalled Performance

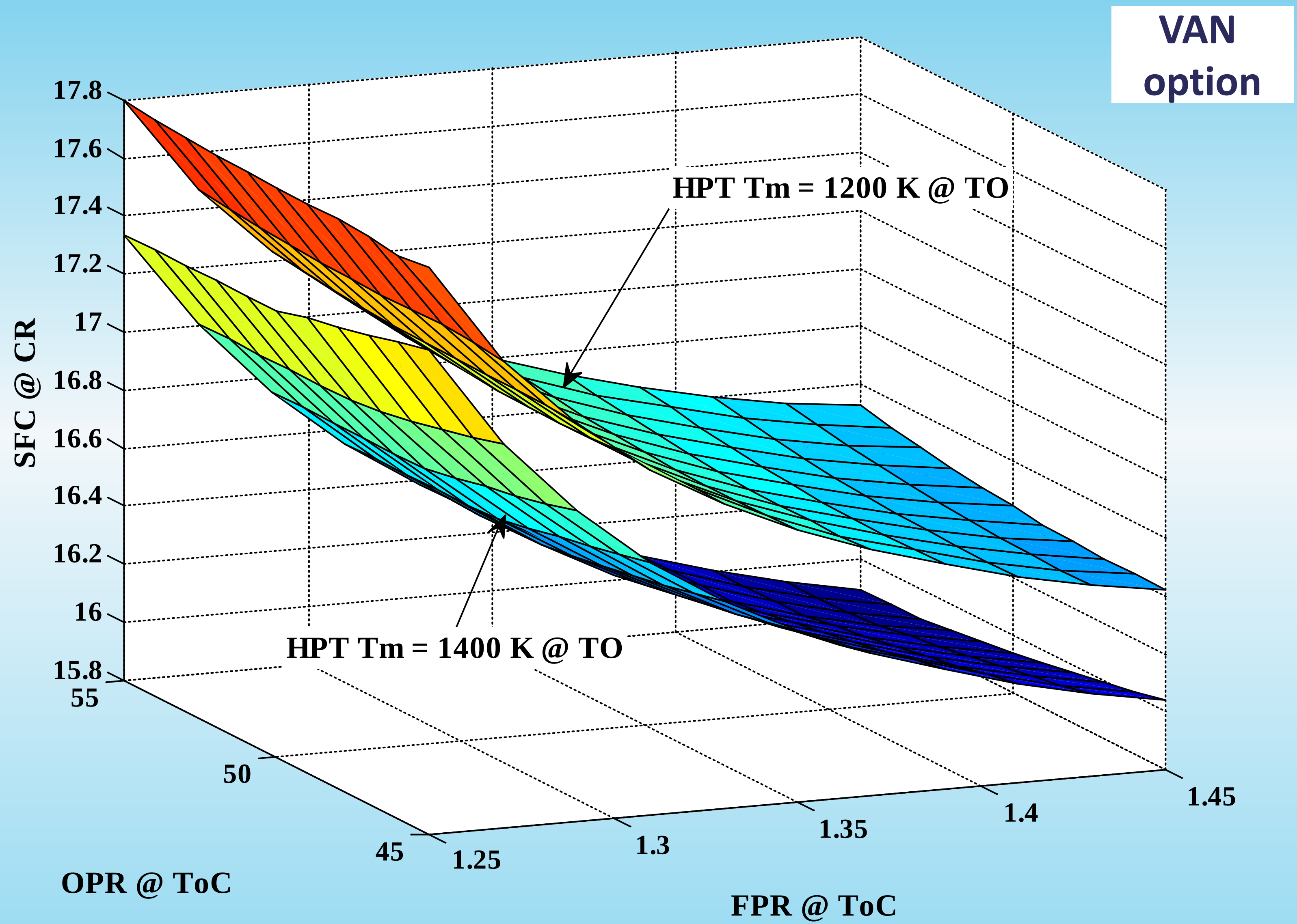
@$SFC_{min,1200}$:FPR=1.29, OPR=49, BPR=22
Wc=15%

@$SFC_{min,1400}$:FPR=1.31, OPR=51, BPR=23.3
Wc=4.7%

VAN option

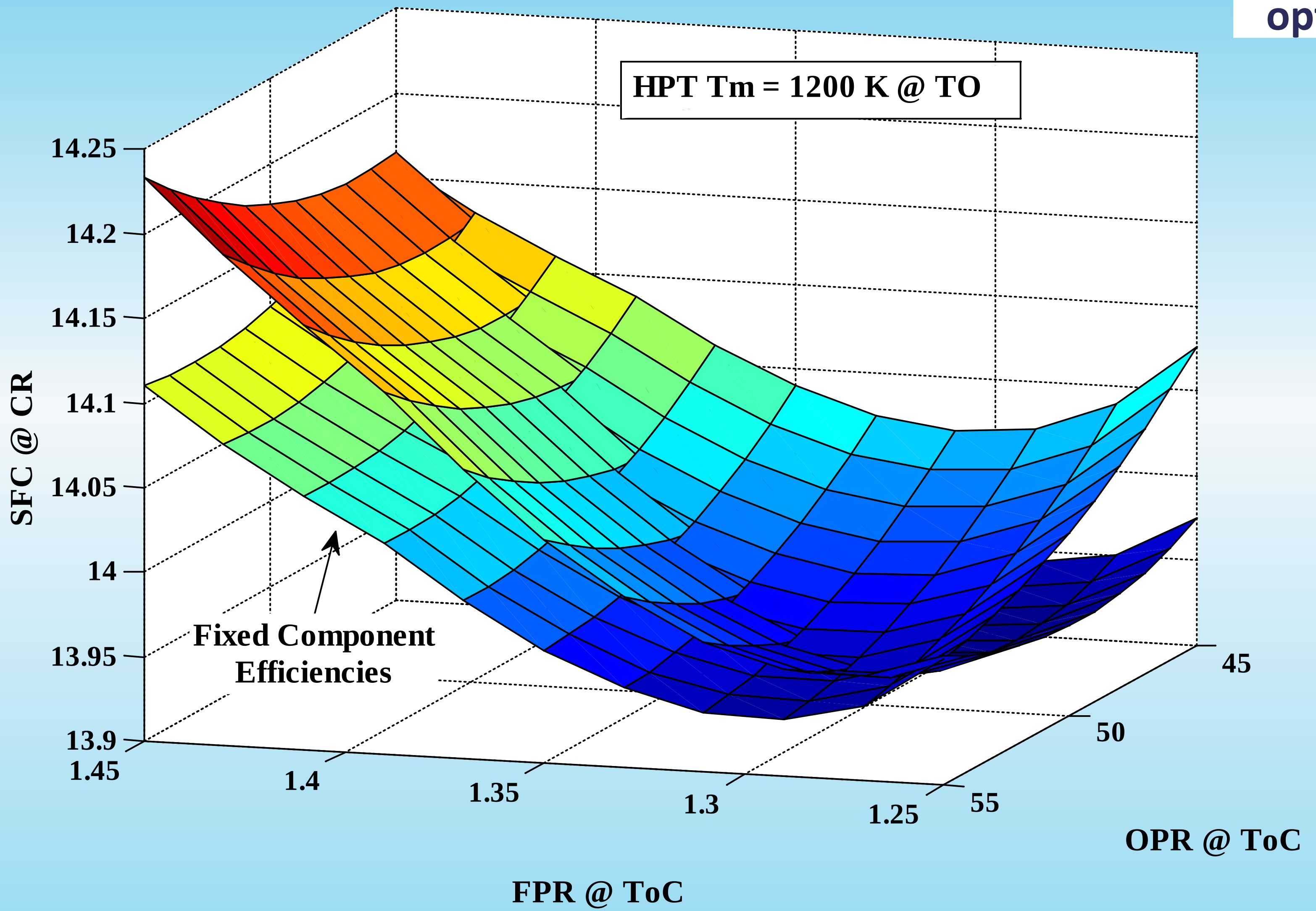


Parametric Analysis: Installed Performance



Parametric Analysis: Design Efficiency Effects

VAN option



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Summary

- An **integrated approach** was presented combining at the same modelling level and within the same commercial simulation environment 0D thermodynamic with 1D aerodynamic calculations, flow path sizing and weight estimation.
- Suitable performance models of the variable geometry technologies considered for UHBR engines (**VAN** and **VPF**) have been developed. **Design point efficiency** of turbomachinery components is calculated according to component design choices and heuristic rules linking efficiency with design parameters. Empirical correlations are also used to estimate the **weight** of engine components. **Installation effects** are considered through a simplified approach correcting net thrust for nacelle drag and engine weight.
- A **multi-point design** methodology is then employed, allowing performance, aerodynamic and structural requirements and constraints to be met simultaneously at different operating points.
- The capabilities developed are demonstrated by first constructing a generic **UHBR GTF** engine performance model.
- **Parametric** MPD simulations are then carried out considering the three main operating points in the commercial aircraft engine flight envelope (take-off, top-of-climb and cruise) for fixed thrust requirements and assuming different levels of turbine cooling technology.

Conclusions

- Based on the assumptions and the range of design variables considered in this study, installation effects do not permit the SFC benefit of UHBR engines to be translated into fuel burn benefit. More detailed models for calculating engine weight and nacelle drag than the ones used in this study are required to determine the BPR/FPR values beyond which this conclusion applies.
- Assumptions/Considerations
  - Gearbox oil cooler
  - VAN nozzle coefficients
  - Constant bypass duct pressure drop
  - Pressure ratio split between the LP and HP compressors and number of stages
- The current multi-disciplinary implementation framework it can be easily extended to include other **modules** such as emissions, noise, lifing and maintenance.
- The integration of an **aircraft** performance tool will then allow design space exploration and multidisciplinary optimisation assessments at aircraft mission level.
- The integrated procedure can be further developed to address **operability** aspects related to **transient** operation and **control system** definition.

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