Direct Integration of Axial Turbomachinery Preliminary Aerodynamic Design Calculations in Engine Performance Component Models

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DEMOS

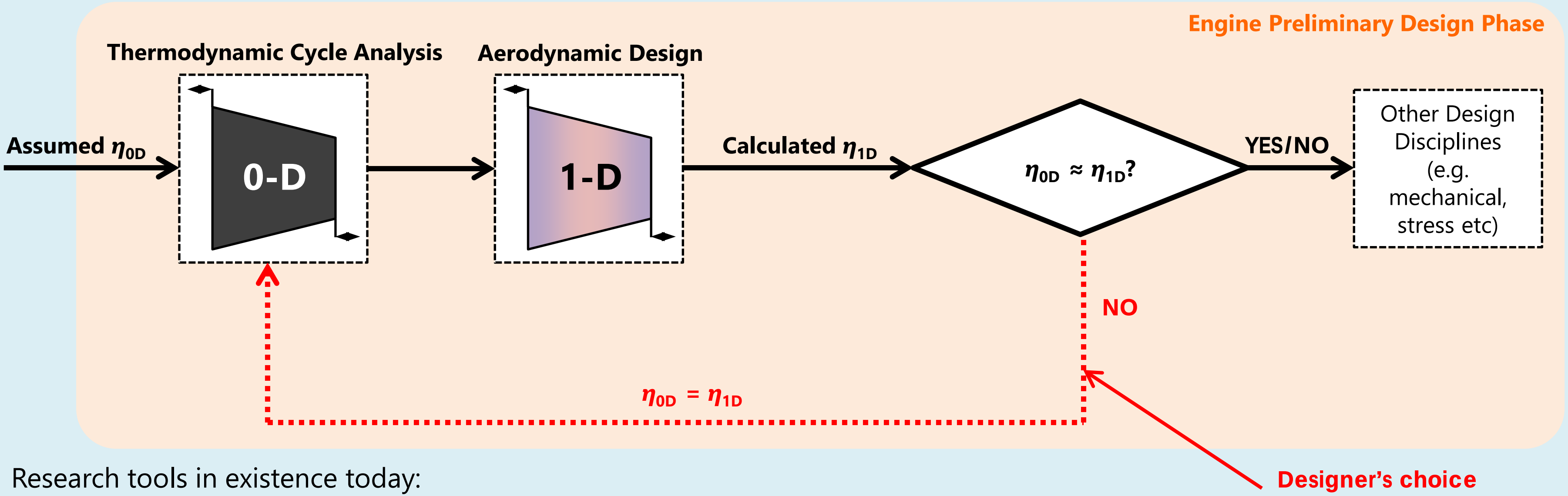
Developing advanced Engine Multi-disciplinary Optimization Simulations

DEMOS Objective

The project DEMOS objective is to develop a modular, flexible and extensible multi-disciplinary **framework** to undertake design space exploration and multidisciplinary optimization assessments of novel aircraft engine concepts:

- **Development of advanced modelling and simulation tools for preliminary design studies of novel aircraft engine concepts**
- **Integration of tools and design processes under the same, commercial, and user-friendly modelling and simulation environment**

Research State of the Art



Research tools in existence today:

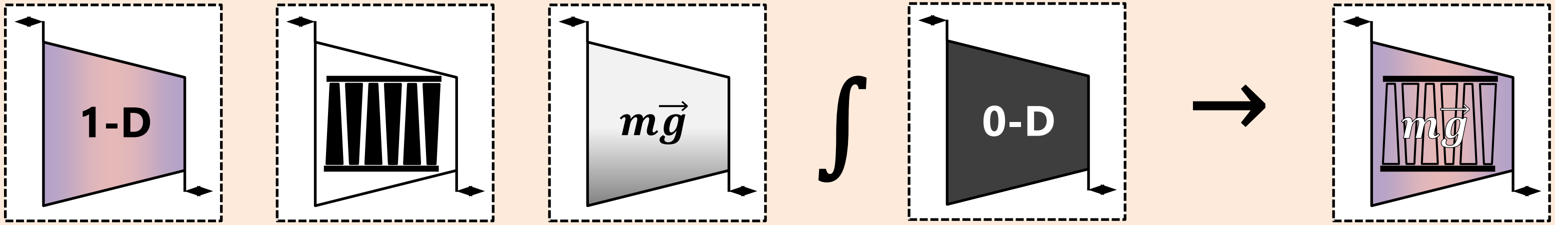
- **Modular** and **iterative** philosophy (e.g. EDS[1], TERA[2])
- 0D, 1D models from **disparate sources** and/or **proprietary nature**
- **Expert-level user** to set-up the engine model and calculation sequence

[1]Kirby, M. and Mavris, D. "The Environmental Design Space". 26th International Congress of the Aeronautical Sciences. ICAS-2008-4.7.3. Anchorage, Alaska, USA, 14-19 September, 2008.
[2]Ogaji, S. Pilidis, P., and Sethi, V. "Advanced Power Plant Selection: The TERA (Techno-economic Environmental Risk Analysis) Framework". 19th ISABE Conference. ISABE-2009-1115. Montreal, Canada, 7-11 September, 2009.

Scope of Paper

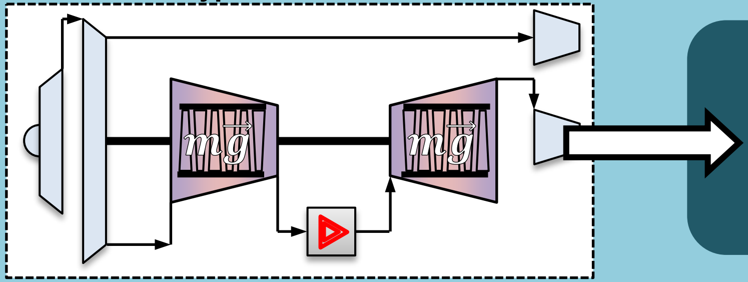
In the context of **DEMOS** project, existing performance models for axial-flow, multistage compressors and turbines:

Aerodynamic Design | **Flowpath Sizing** | **Weight Estimation** | **Thermodynamic Performance** | **New Turbomachinery Components**



Same modelling level

HBR GTF with bypass VAN



Multi-Point Design
@TO, CR, ToC

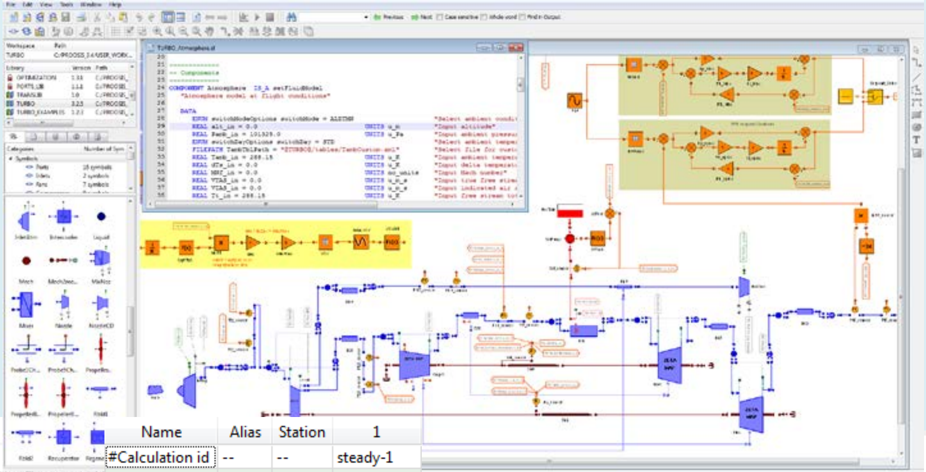
- Performance requirements
- Aerodynamic constraints
- Mechanical constraints
- Thermal constraints

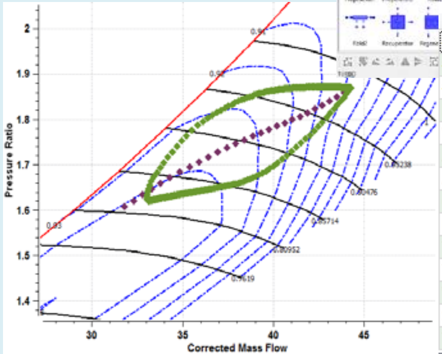
PROOSIS Simulation Environment

Modelling Tool

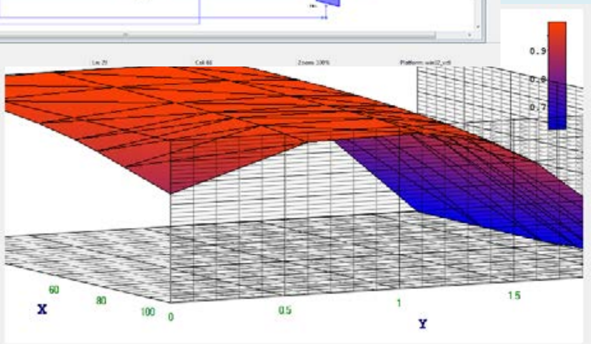
PROOSIS (**PR**opulsion **O**bject-**O**riented **SI**mulation **S**oftware)

- **Object-Oriented**
- **Steady State**
- **Transient**
- Mixed-Fidelity
- Multi-Disciplinary
- Distributed
- **Multi-Point Design**
- Off-Design
- Test Analysis
- Diagnostics
- Sensitivity
- Optimization
- Deck Generation
- Version Control





Name	Alias	Station	1
#Calculation id	--	--	steady-1
#Status	--	--	STEADY_OK
#ESI	--	--	0
FN (N)	--	--	63008.679
WF (kg/s)	--	--	1.70123433
Amb.alt (m)	alt	--	11000
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



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Methodology

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3. Validation Cases

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2. The MPD Structure
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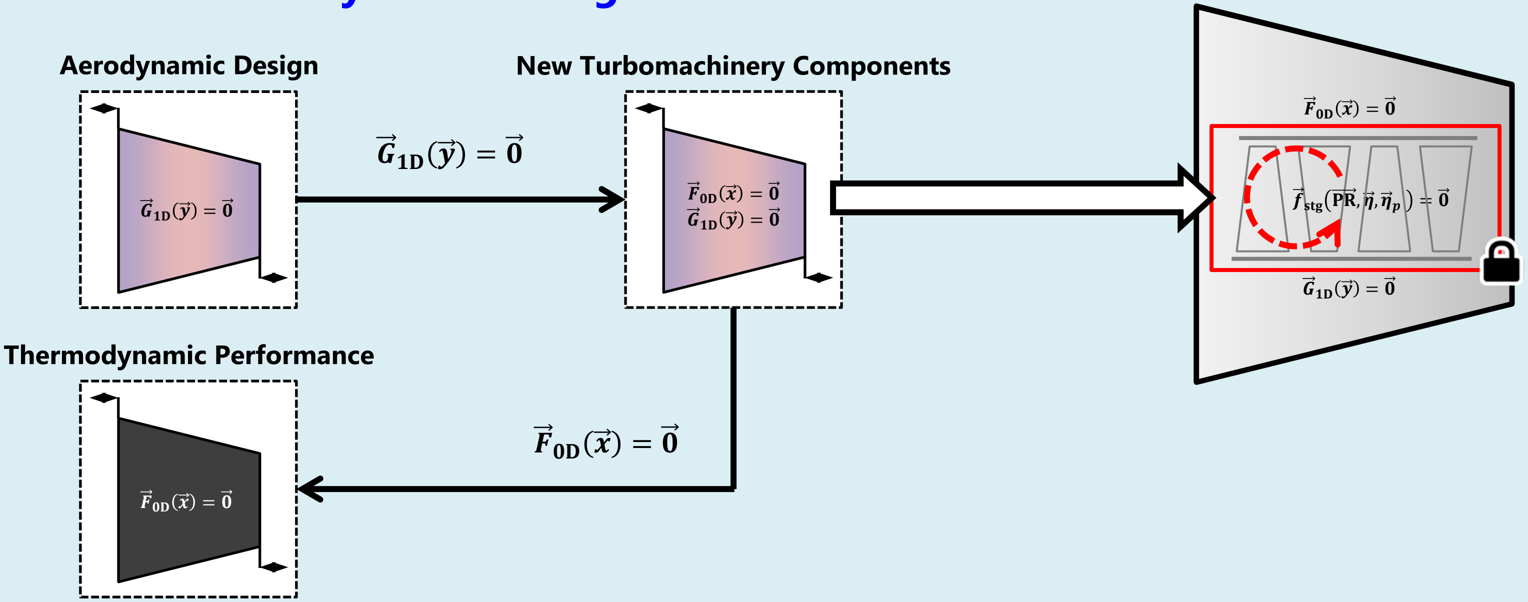
4. Design Space Exploration Results
5. Engine Flowpath Visualization

Summary & Conclusions

Performance–Aerodynamics Integration



- **Consistent and single-step preliminary design procedure**
- No need for continuous data interchange between 0D and 1D
- Mathematical models @component and @engine level remain unchanged
- Same level of robustness and speed of execution as for 0D models

Aerodynamic Design & Flowpath Sizing

The aerodynamic design is accomplished through:

- **Stage-by-stage**, **mean-line** calculation with variable gas properties
- Possibility for different mean-line distributions
- Possibility to specify different flow coefficient (φ), stage loading (ψ), and stage reaction (Λ) distributions to establish velocity triangles @D_m; To establish flow quantities @D_h + @D_t the free vortex flow assumption is used
- Aerothermodynamic calculations accounting for compressor bleeds
- Aerothermodynamic turbine design integrated with row-by-row cooling capability

After the aerodynamic design has been completed and the stagewise D_h + D_t are known:

- Axial sizing of component stages is performed assuming linear distribution of first and last stage blade *AR* and axial gapping and a simple geometrical concept[3]
- Component overall flowpath geometry is established by axial superposition of component stages

✓ **Both aerodynamic design + flowpath sizing use only a small number of physical and geometrical inputs**

[3]Mattingly, J. D. Elements of Gas Turbine Propulsion. AIAA Education Series (1996).

Calculation of stagewise isentropic efficiency (η):

Losses methods

Lewis'[4] method for compressor stages:

$$\eta = 1 - \frac{1}{2\psi}\left\{\zeta_R\left[\varphi^2 + \left(\Lambda + \frac{\psi}{2}\right)^2\right] + \zeta_S\left[\varphi^2 + \left(1 - \Lambda + \frac{\psi}{2}\right)^2\right]\right\}$$

Glassman's[5] method for uncooled turbine stages:

$$\eta_{\mathrm{uncooled}} = \frac{1}{1 + \frac{1}{2}A\psi}$$

Semi-empirical methods

Glassman's[6] method for compressor stages:

$$\vec{f}\left(\mathrm{PR}, \eta_p, \eta\right) = \vec{0}$$

Aungier's[7] method for uncooled turbine stages:

$$\eta_{\mathrm{uncooled}} = \mathrm{TF} \times \left[\eta_{\mathrm{optimum}} - K\left(\varphi - \varphi_{\mathrm{optimum}}\right)^2\right]$$

Glassman's[8] correction for cooled turbine stages:

$$\eta_{\mathrm{cooled}} = \left(1 - \delta_R m_R - \delta_S m_S\right) \times \eta_{\mathrm{uncooled}}$$

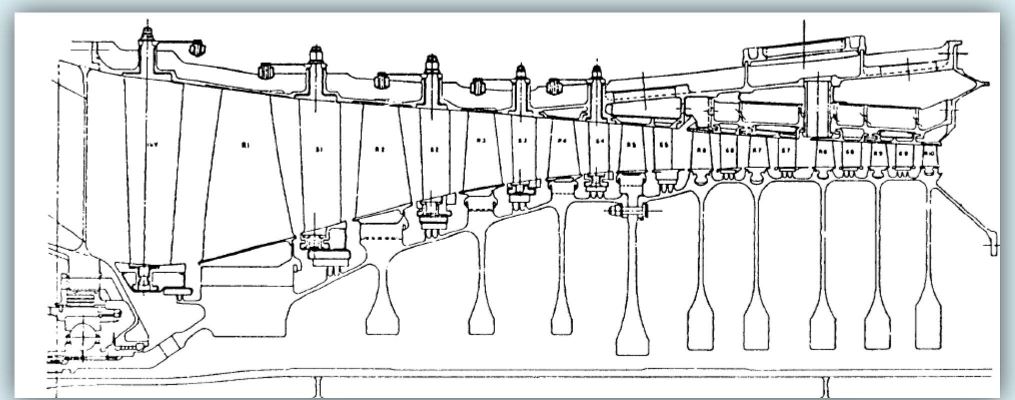
Other ways to establish component overall efficiency:

- **Directly imposed**
- **Samuelsson et al.'s[9] method for overall polytropic efficiency (η_p) estimation:**

$$\eta_p = f\left(\text{Component Size}, \text{Entry Into Service Year}, \text{Reynolds Number}, \text{Stage Loading}\right)$$

[4]Lewis, R. I. Turbomachinery Performance Analysis. Elsevier Science and Technology Books (1996).
[5]Glassman, A. J. "Computer Code for Preliminary Sizing Analysis of Axial-Flow Turbines". CR-4430. NASA. 1992.
[6]Glassman, A. J. "Users Manual for Updated Computer Code for Axial-Flow Compressor Conceptual Design". CR-189171. NASA. 1992.
[7]Aungier, R. H. Turbine Aerodynamics: Axial-Flow and Radial Inflow Turbine Design and Analysis. ASME Press, New York (2005).
[8]Glassman, A. J. "Enhanced Capabilities and Updated Users Manual for Axial-Flow Turbine Preliminary Sizing Code TURBAN". CR-195405. NASA. 1994.
[9]Samuelsson, S., Kyprianidis, K. G., and Grönstedt, T. "Consistent Conceptual Design and Performance Modeling of Aero Engines". Proceedings of ASME Turbo Expo. GT2015-43331. Montreal, Canada, June 15-19, 2015.

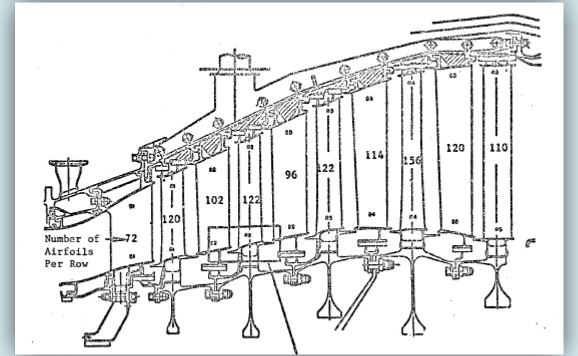
Validation Cases



Compressor component

- **NASA/GE E³ HP Compressor was used[9,10]**
- 10-Stage
- High-speed
- High-aerodynamic loading
- Efficiency goal: 85.7%

Turbine component

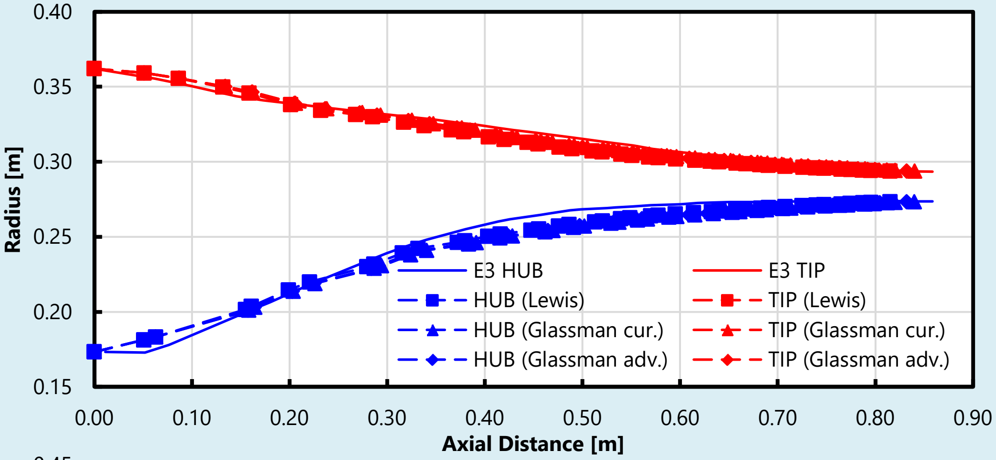


- **NASA/GE E³ LP Turbine Block II Scaled Air-Model was used[11]**
- 5-Stage
- High-aerodynamic loading
- Measured efficiency: 92.0%

[9]Holloway, P. R., Knight, G. L., Koch, C. C., and Shaffer, S. J. "Energy Efficient Engine High Pressure Compressor Detail Design Report". CR-165558. NASA. 1982.
[10]Cline, S. J., Fesler, W., Liu, H. S., Lovell, R. C., and Shaffer, S. J., "High Pressure Compressor Component Performance Report". CR-168245. NASA. 1983.
[11]Bridgeman, M. J., Cherry, D. G., and Pedersen, J. "NASA/GE Energy Efficient Engine Low Pressure Turbine Scaled Test Vehicle Performance Report". CR-168290. NASA. 1983.

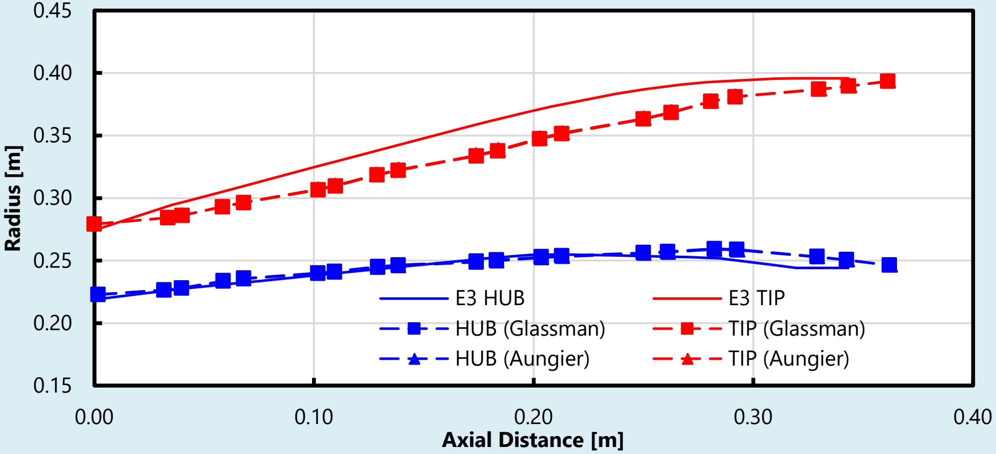
Compressor component

Method	Calculated Efficiency	Relative Error from Goal
Lewis (Losses)	85.01%	−0.81%
Glassman cur.	84.41%	−1.51%
Glassman adv.	86.51%	+0.95%



Turbine component

Method	Calculated Efficiency	Relative Error from Measured
Glassman (Losses)	91.38%	−0.68%
Aungier **(TF=1)**	89.02%	−3.24%



✓ **Sufficient agreement**, using existing turbomachinery components that have been through all the stages of the development course

Application Example

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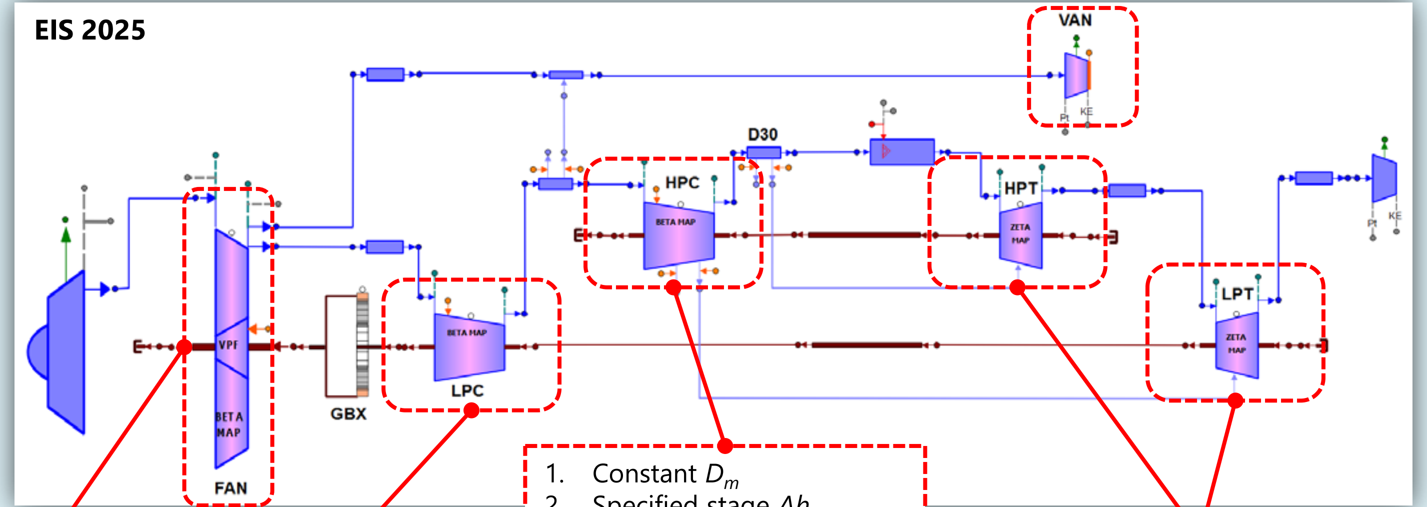
Summary & Conclusions

The HBR GTF Engine Model with Bypass VAN



$\eta_p = f(\text{FPR})$[12]

1. Constant D_h
2. Constant ψ
3. Linear φ
4. Specified $\alpha_1 \rightarrow \Lambda$
5. Losses method for η

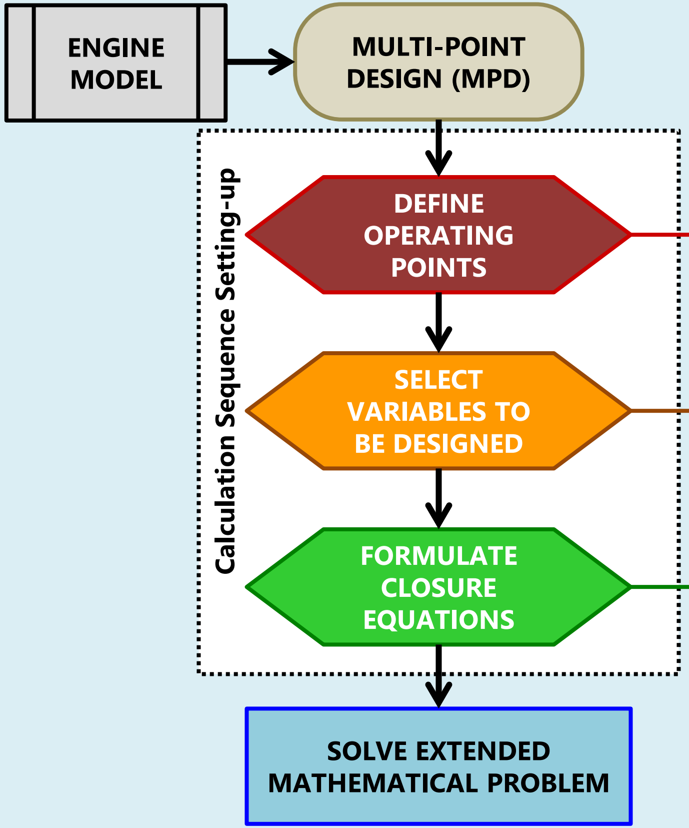
1. Constant D_m
2. Specified stage Δh_t
3. Linear φ
4. Specified $\alpha_1 \rightarrow \Lambda$
5. Losses method for η

1. Linear D_m
2. Constant ψ
3. $\Lambda = 0.5$ (symmetrical velocity triangles)
4. Aungier's method for η

- ✓ 1_G_4_8_2_3
- ✓ Fixed fan diameter
- ✓ Fixed sFN **@ToC**
- ✓ Off-design performance from suitable maps scaled accordingly during design calculation

[12]Felder, J. L., Kim, H. D., Brown, G. V., and Chu, J. "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion Systems". AIAA-2011-300. 2011.

The MPD Structure



ToC, TO, CR (set flight and ambient conditions)

Mathematical model boundaries at every OP (e.g.):

- Fuel mass flow rate (to match specified engine thrust) **@ToC, TO, CR**
- VAN % area change (to match VAN operability criterion) **@ToC, TO, CR**

Component attributes at individual OPs (e.g.):

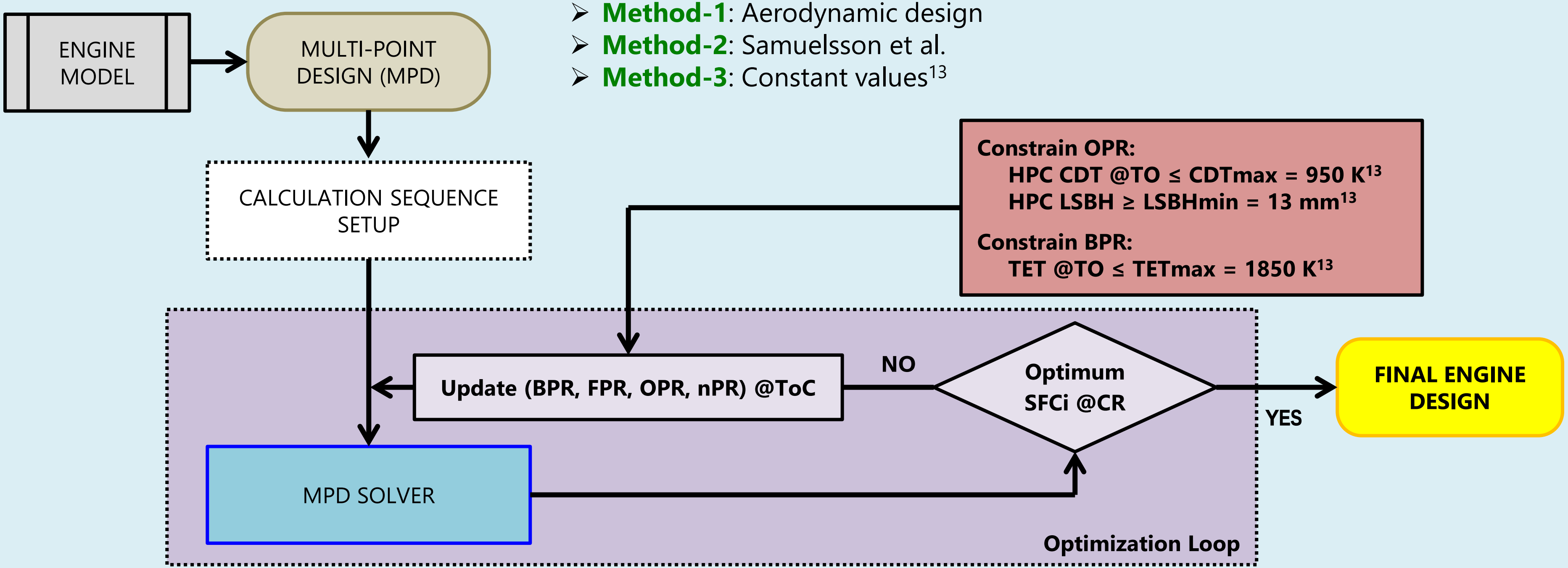
- Scaling factors of all turbomachinery maps **@ToC**
- HPT cooling flow fractions for all blading rows **@TO**

- FN = Specified FN **@ToC, TO, CR**
- BPR, FPR, OPR, nPR = (Calculated or specified) BPR, FPR, OPR, nPR **@ToC**
- **For compressors: η_p = (Calculated or specified) η_p @CR**
- **For turbines: η = (Calculated or specified) η @CR**

MPD Optimization Runs

Turbomachinery efficiencies **@CR** are established through three different methods:

- **Method-1**: Aerodynamic design
- **Method-2**: Samuelsson et al.
- **Method-3**: Constant values[13]



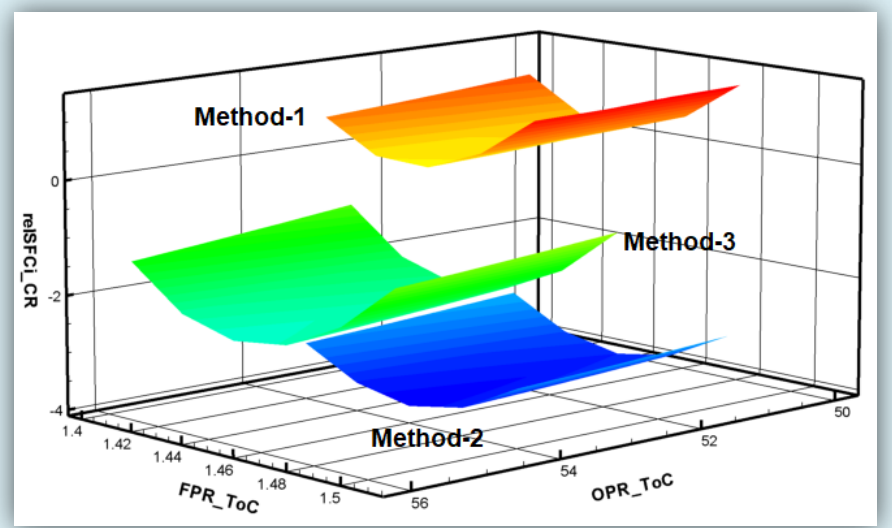
[13]Larson, L., Grönstedt, T. , and Kyprianidis K. G. "Conceptual Design and Mission Analysis for a Geared Turbofan and an Open Rotor Configuration". Proceedings of ASME Turbo Expo. GT2011-46451. Vancouver, British Columbia, Canada, June 6-10, 2011.

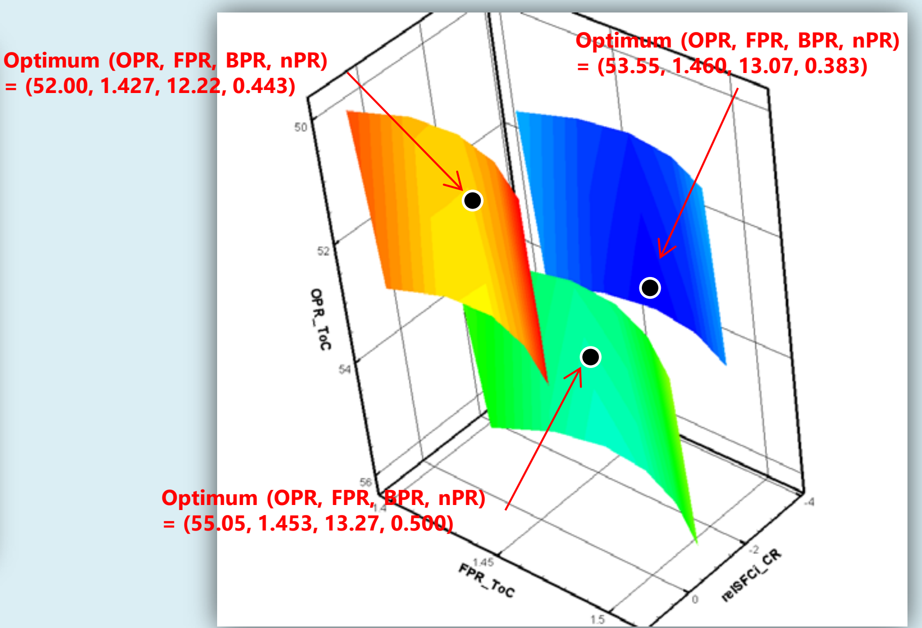
OP	Parameter	Method-1	Method-2	Method-3
ToC	**OPR [-]**	**52.00**	**53.55**	**55.05**
	BPR [-]	12.22	13.07	13.27
	FPR [-]	1.427	1.460	1.453
	nPR [-]	0.443	0.383	0.500
CR	EP13 [-]	0.948	0.950	0.924
	EP25 [-]	0.914	0.919	0.920
	EP3 [-]	0.905	0.917	0.925
	E45 [-]	0.924	0.920	0.921
	E5 [-]	0.933	0.952	0.946
	Transfer Efficiency [-]	0.874	0.882	0.859
	Core Efficiency [-]	**0.559**	**0.567**	**0.572**
	Propulsive Efficiency [-]	0.804	0.817	0.816
	SFCi [g/kNs]	15.932	15.329	15.578
TO	**CDT [K]**	**950.0**	**950.0**	**950.0**
	TET [K]	1760.6	1790.9	1850.0
	VAN change [%]	8.24	6.68	6.98
N/A	W [kg]	2594	2622	2496
	Gear ratio [-]	2.80	2.60	2.65
	HPC LSBH [mm]	16.2	13.9	16.4

=CDTmax

Design Space Exploration Results

Engine design space is explored through **parametric MPD runs** varying (FPR, OPR) @ToC, and each time (BPR, nPR) @ToC are again optimized for minimum SFCi @CR:

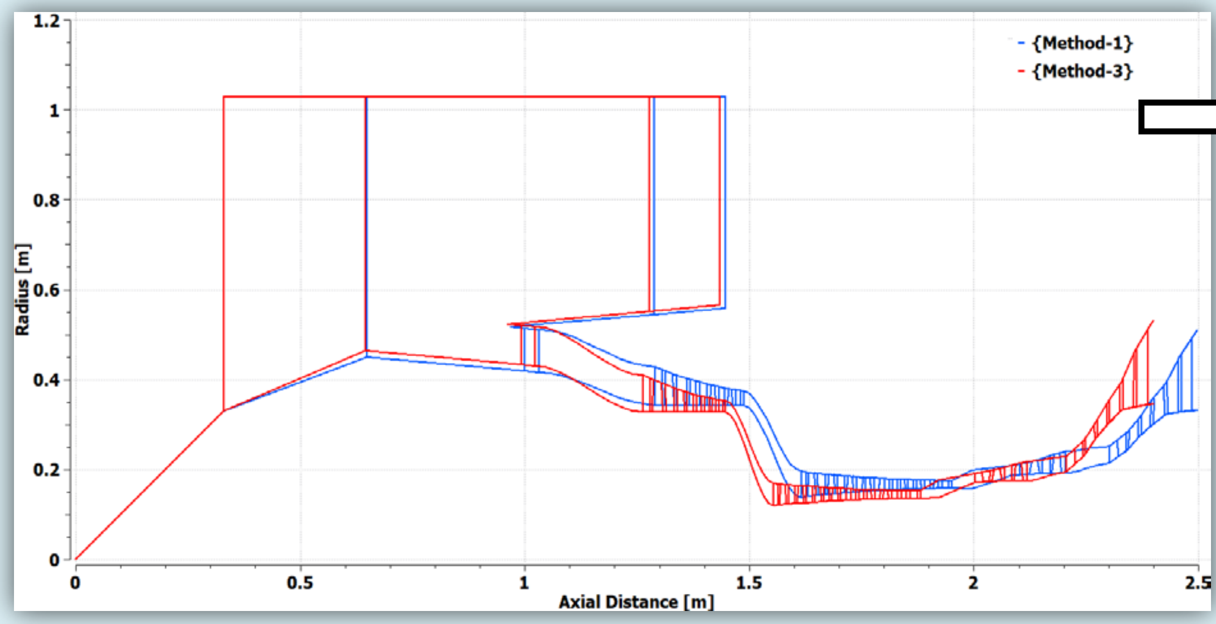




- ✓ Design spaces of similar shape
- ✓ Boundaries and optimum solution depend on method to establish turbomachinery efficiencies @CR
- ✓ Installed performance differences up to ~3% between different methods

Engine Flowpath Visualization

Through the aerothermodynamic design is possible to visualize the engine flowpath geometry:



Constrained MPD and flowpath sizing calculations < 3 seconds in a typical home desktop PC

- Method-1: Geometry calculated for optimum (OPR, FPR, BPR, nPR) @ToC = (52.00, 1.427, 12.22, 0.443)
- Method-3: Geometry calculated for optimum (OPR, FPR, BPR, nPR) @ToC = (55.05, 1.453, 13.27, 0.500)
- **Method-1 to establish turbomachinery efficiencies @CR**

Summary & Conclusions

Summary & Conclusions

- A consistent, single step modelling process was presented that combines turbomachinery 0D thermodynamic performance with 1D aerodynamic design and flowpath sizing, at the same modelling level and under the same user-friendly simulation environment.

- Design point efficiency of turbomachinery components can be established using losses or semi-empirical correlations, through a stage-by-stage design approach.

- Constrained MPD Optimization and Parametric runs were then carried out on a HBR GTF with bypass VAN, allowing performance requirements and aerodynamic, thermal, and structural constraints to be accounted for simultaneously at three different operating conditions.

  - **MPD runs showed that the optimum design in terms of installed performance as well as engine geometry depend on the method for obtaining the turbomachinery design-point efficiencies.**

  - **MPD runs also showed that installed performance could present significant differences between the different methods used to establish turbomachinery design-point efficiencies.**

✓ Future work includes the integration of modules for noise, emissions, lifing, and maintenance calculations, and the simultaneous optimization of both aircraft and engine at mission level.

Questions?

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