



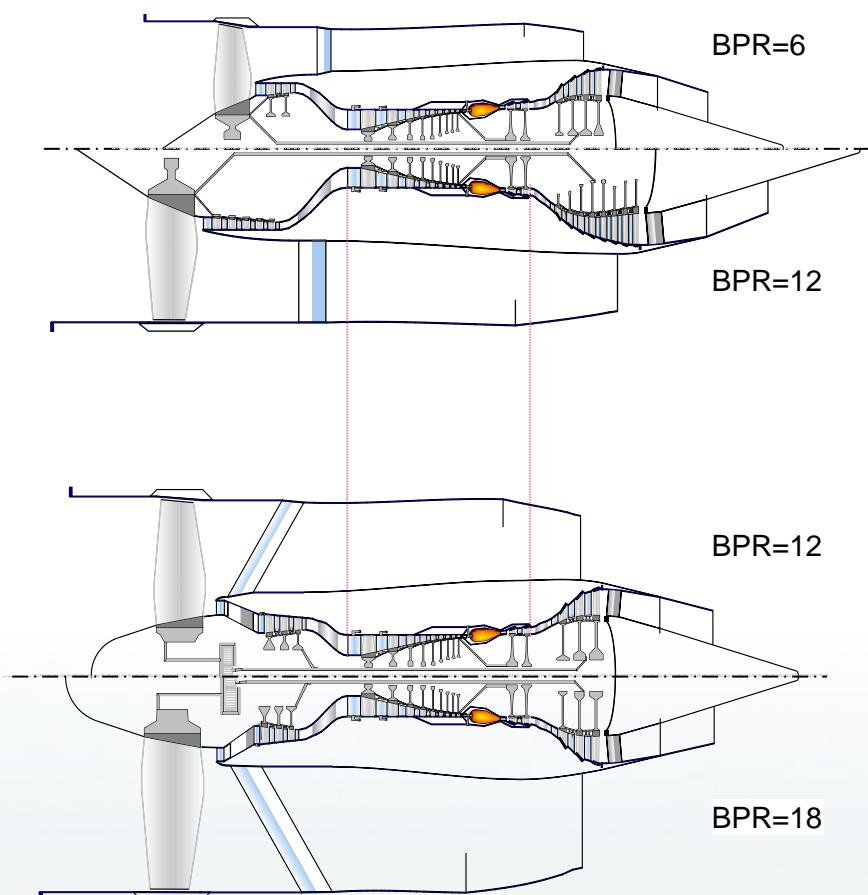
Gas Turbine Design and Performance

ENGINE FAMILIES





An Engine Family is...



- A series of units all based on a common core.
- The siblings of an engine family are called derivatives.
- The derivative engines generate higher or lower levels of thrust.



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Thrust Growth of a Business Jet Engine

- Business jet engines have rather low OPR and moderate T_4
- Fuel consumption is less important than engine acquisition cost

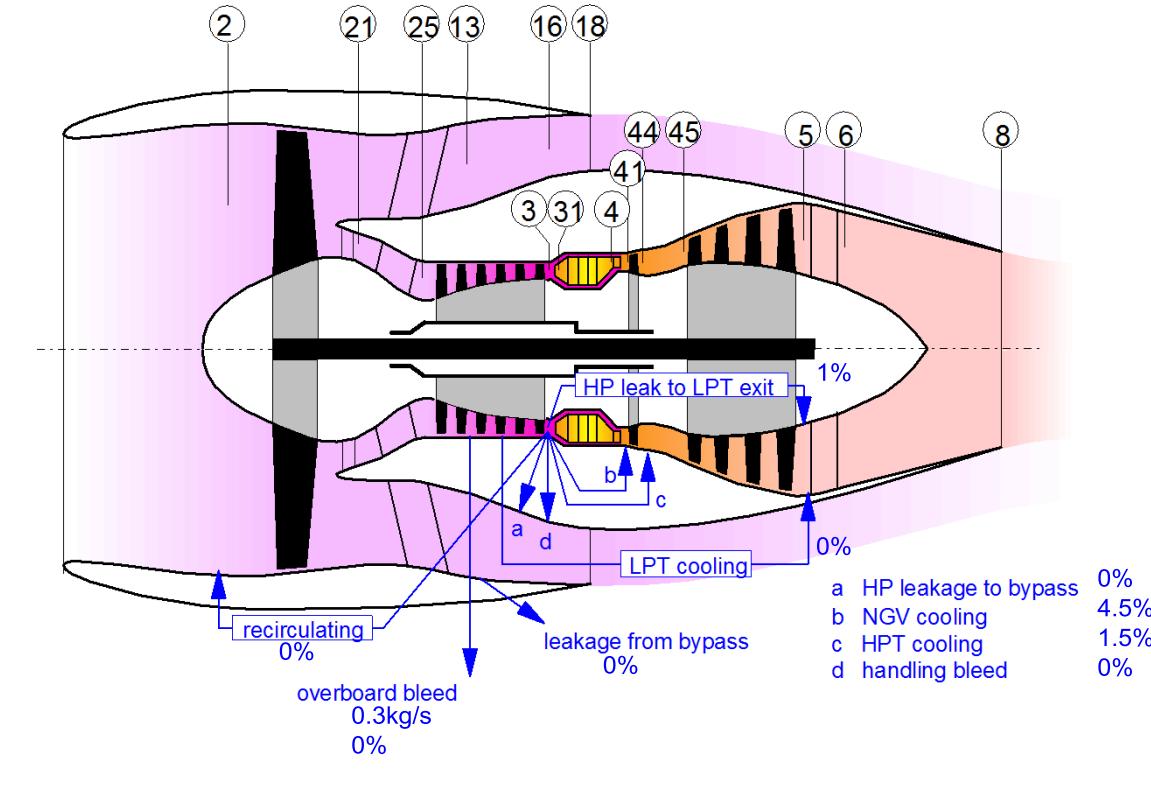
The target:

- Increase Thrust by 25%



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Baseline Engine Configuration





Baseline Engine

Cycle Reference Point

Max Climb, 11km, Mach 0.8, ISA

Station	W kg/s	T K	P kPa	WRstd kg/s		=	3.41	kN
amb		216.65	22.632					
1	22.186	244.44	34.509		TSFC	=	20.1043	g/(kN*s)
2	22.186	244.44	34.509	60.000	WF	=	0.06853	kg/s
13	18.153	294.47	60.818	30.573	BPR	=	4.5000	
21	4.034	297.90	63.842	6.510	S NOx	=	0.2590	
25	4.034	297.90	63.203	6.575	Core Eff	=	0.4472	
3	4.034	646.64	758.439	0.807	Prop Eff	=	0.7496	
31	3.452	646.64	758.439		P3/P2	=	21.98	
4	3.520	1350.00	735.686	1.049	P2/P1	=	1.0000	
41	3.702	1318.27	735.686	1.090	P16/P13	=	0.9800	
43	3.702	978.49	172.646		P25/P21	=	0.9900	
44	3.762	973.45	172.646		P45/P44	=	0.9800	
45	3.762	973.45	169.193	4.141	P6/P5	=	0.9800	
49	3.762	710.16	41.094		A8	=	0.06443	m²
5	3.762	710.16	41.094	14.562	A18	=	0.13248	m²
8	3.802	709.51	40.272	15.012	P8/Pamb	=	1.77943	
18	18.153	294.47	59.602	31.197	P18/Pamb	=	2.63351	
Bleed	0.300	646.64	758.438		WBld/W25	=	0.07437	

Efficiencies:	isentr	polytr	RNI	P/P	CD18	=	0.97600	
Outer LPC	0.8600	0.8707	0.413	1.762	XM8	=	0.95562	
Inner LPC	0.8800	0.8899	0.413	1.850	XM18	=	1.00000	
HP Compressor	0.8600	0.8985	0.600	12.000	V18/V8,id=	0.81000		
Burner	0.9995			0.970	Loading	=	100.00	%
HP Turbine	0.8800	0.8598	1.225	4.261	e444 th	=	0.87427	
LP Turbine	0.9001	0.8822	0.399	4.117	PWX	=	50.00	kW

HP Spool mech	Eff 0.9900	Nom Spd	32000	rpm	WCHN/W25	=	0.04500	
LP Spool mech	Eff 1.0000	Nom Spd	13497	rpm	WCHR/W25	=	0.01500	

					WLc1/W25	=	0.00000	





Designing a Derivative

- The many constraints imposed by the given gas generator make the cycle selection for the derivative engine a challenge.
- Traditionally the design space is explored with extensive parametric studies.
 - This is easy if there are only two or three design parameters.
 - If the number of design variables exceeds three or four this becomes time consuming and difficult.
- We search for the optimum engine design with the help of numerical optimization.



Boundary Conditions

- The maximum permissible spool speed is very much limited by the tolerable disk stress.
- The aerodynamics and burner exit temperature differ.
- The flow capacity of compressors and turbines can vary within the same annulus
 - re-stagger or re-design blades and vanes.
- In an ideal world the gas generator of an engine family would consist of identical parts. In reality the cores of the engines are similar, but not identical.



Sizing Operating Points

Aerodynamics: Max Climb, 11km, Mach 0.8, ISA

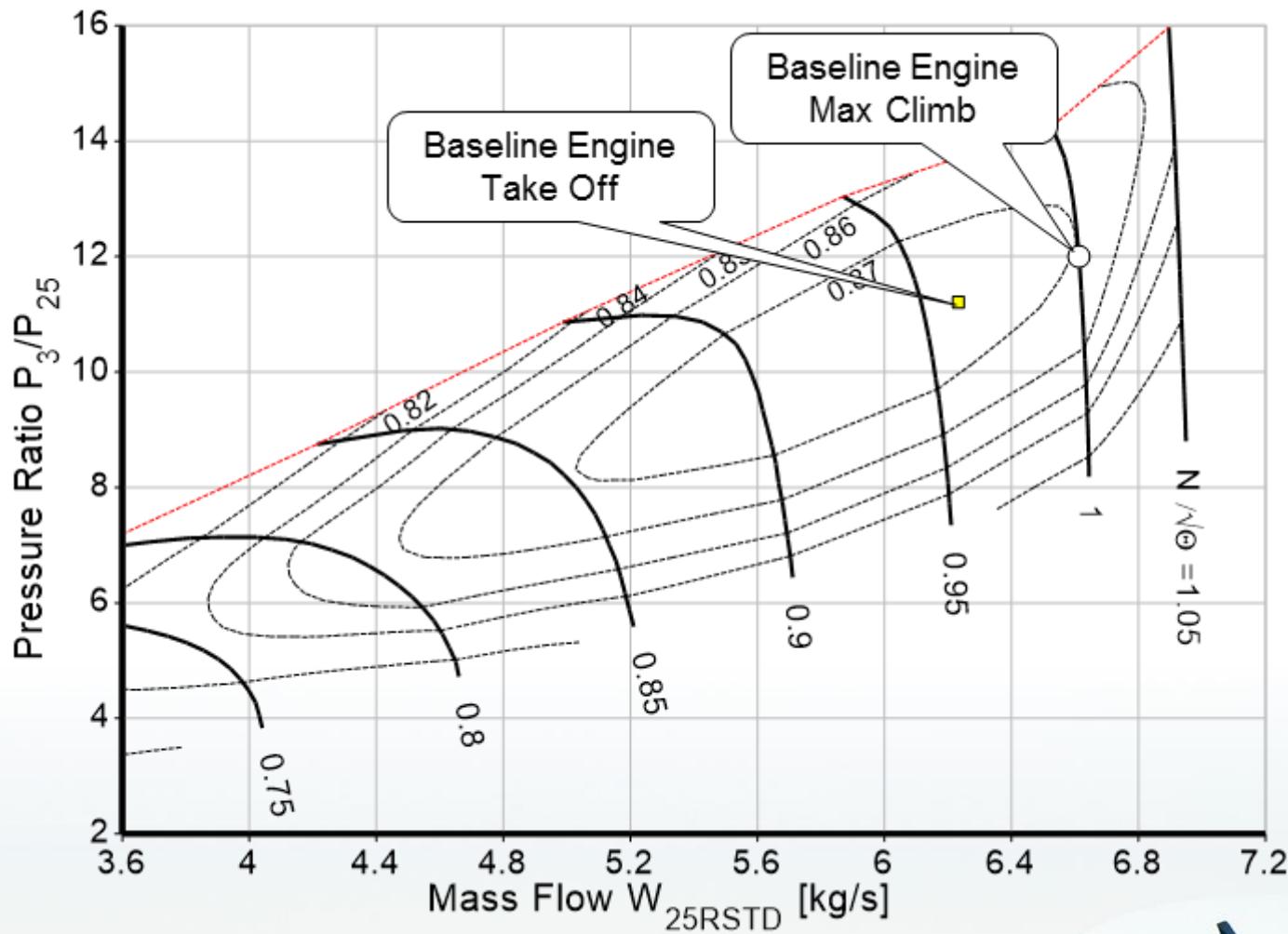
Mechanics: Take Off, SL, Mach 0.2, ISA+15K

	Max Climb	Hot Day Take Off
N_H [%]	100	105
T_{25} [K]	297.9	356.06
T_3 [K]	647	743
T_4 [K]	1350	1416
T_{45} [K]	973	1027
F_N [kN]	3.41	12.0





Gas Generator Compressor Map



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Corrected HPC Speed

- The map contains relative $N_H/\sqrt{\Theta_{25}}$ values
- At the baseline engine Max Climb point is

$$\frac{N_H/\sqrt{\Theta_{25}}}{(N_H/\sqrt{\Theta_{25}})_{ref}} = 1$$

- The reference corrected speed is

$$\left(\frac{N_H}{\sqrt{\theta_{25}}}\right)_{ref} = \frac{32000rpm}{\sqrt{\frac{T_{25}}{288.15K}}} = \frac{32000rpm}{\sqrt{\frac{297.9K}{288.15K}}} = 31472rpm$$



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True HP Spool Speed

An example:

If the map is read with

relative corrected speed $N_H/\sqrt{\Theta_{25}} = 0.9604$

and

$T_{25} = 356.06K$ (the hot day Take Off T_{25})

Then

$$N_{H,rpm} = 0.9604 * 31472 rpm * \sqrt{\frac{356.06K}{288.15K}} = 33600 rpm$$

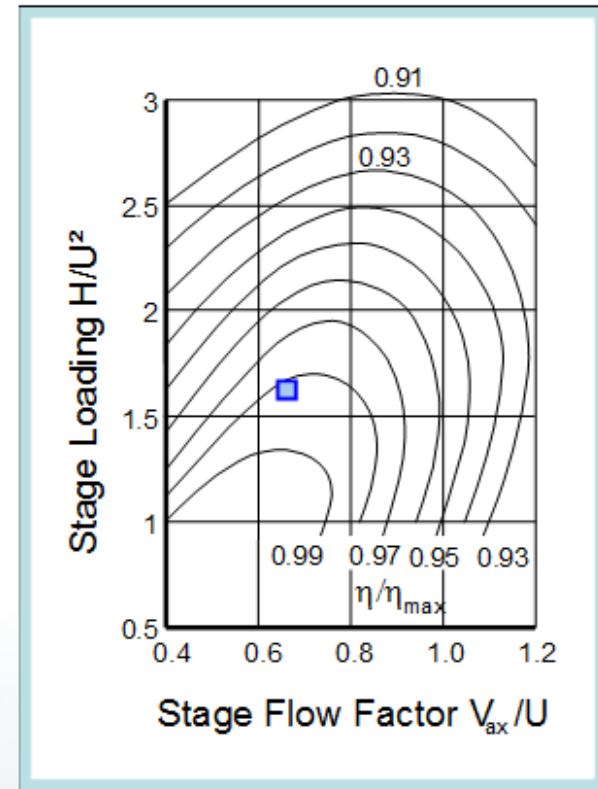
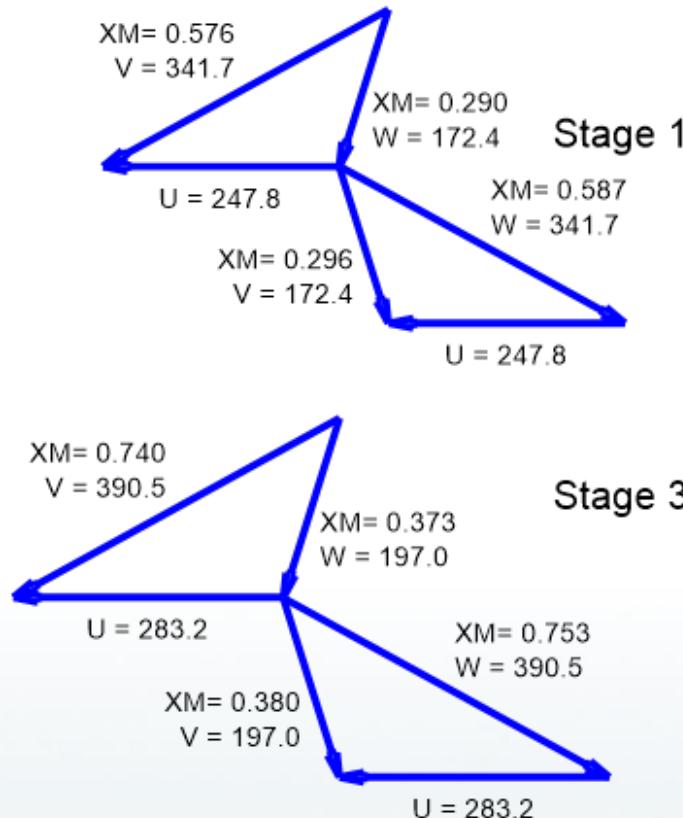
Relative N_H :

$$N_{H,rel} = \frac{33600}{32000} = 1.05$$

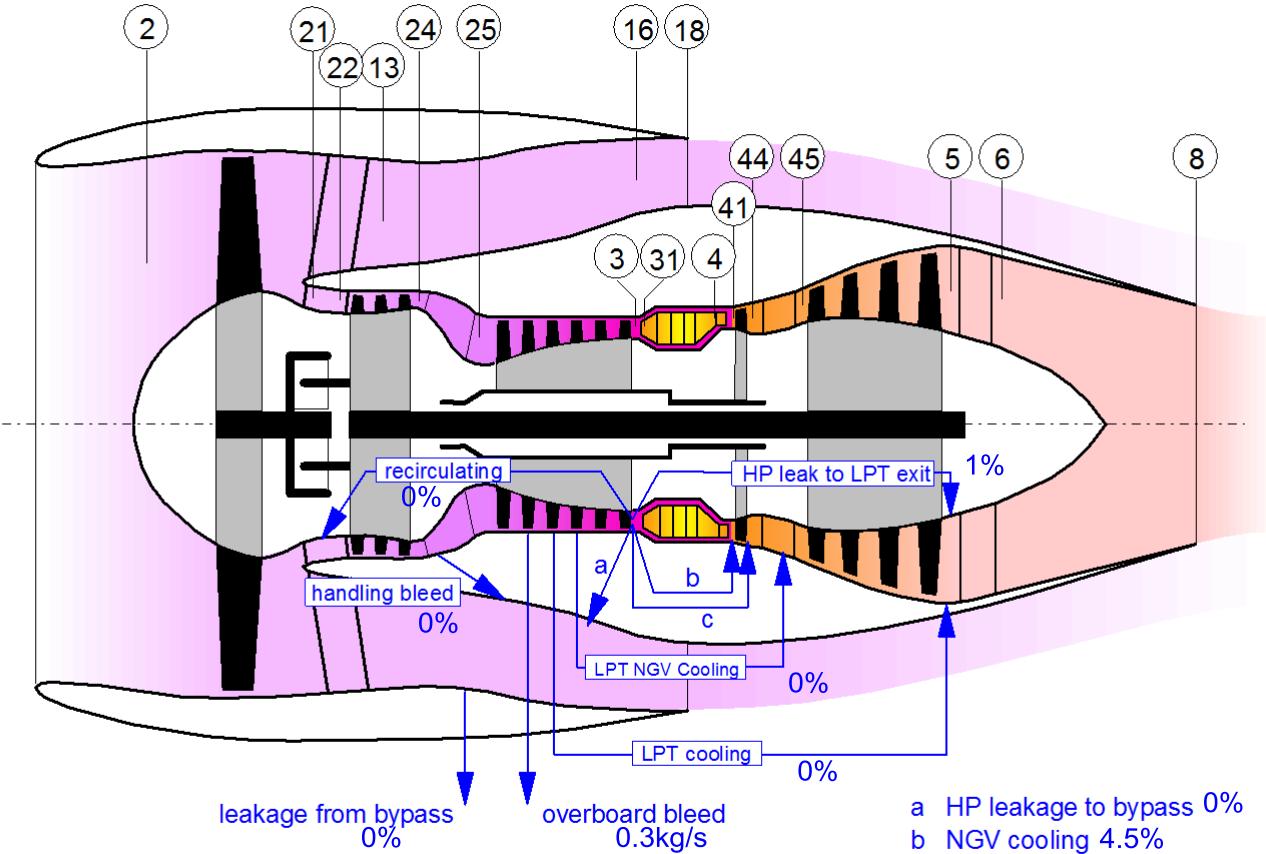




LPT Velocity Triangles for the Baseline Engine



Growth Engine Configuration





Design Variables

		min	max
1	Fan pressure ratio	1.1	1.9
2	Booster pressure ratio	1.4	2.3
3	Bypass ratio	4	6
4	Burner exit temp T_4	1300K	1600K
5	Rel. spool speed N_H	0.9	1.02
6	HPC map coordinate β	0.3	0.8





Design Constraints

1	HP turbine flow capacity	reference value $\pm 5\%$	
2	LP turbine flow capacity	reference value $\pm 5\%$	
3	LP turbine inlet temp T_{45}	$< 1150\text{K}$	hot day take off
4	Compressor exit temp T_3	$< 750\text{K}$	hot day take off
5	Fan tip diameter	$< 0.75\text{m}$	
6	Core spool speed N_H	$<$ reference $+ 1\%$	
7	Max Climb thrust	$> 4.26 \text{ kN}$	$= 3.41\text{kN} + 25\%$
8	Hot day Take Off thrust	$> 15 \text{ kN}$	$= 12\text{kN} + 25\%$



Figure of Merit

Minimize specific fuel consumption (SFC) for Max Climb (11km Mach 0.8 ISA)

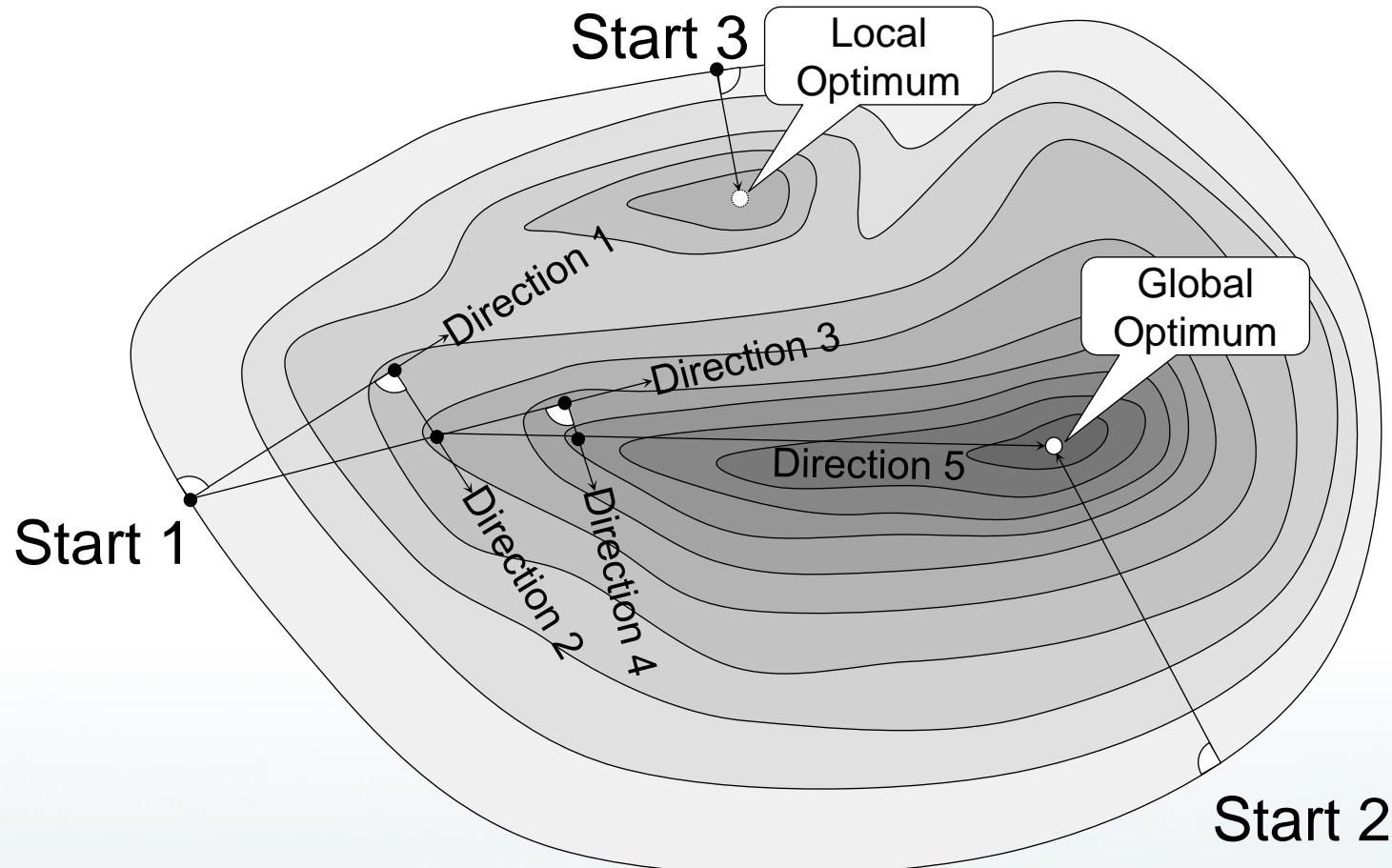
- This automatically results in low cruise SFC



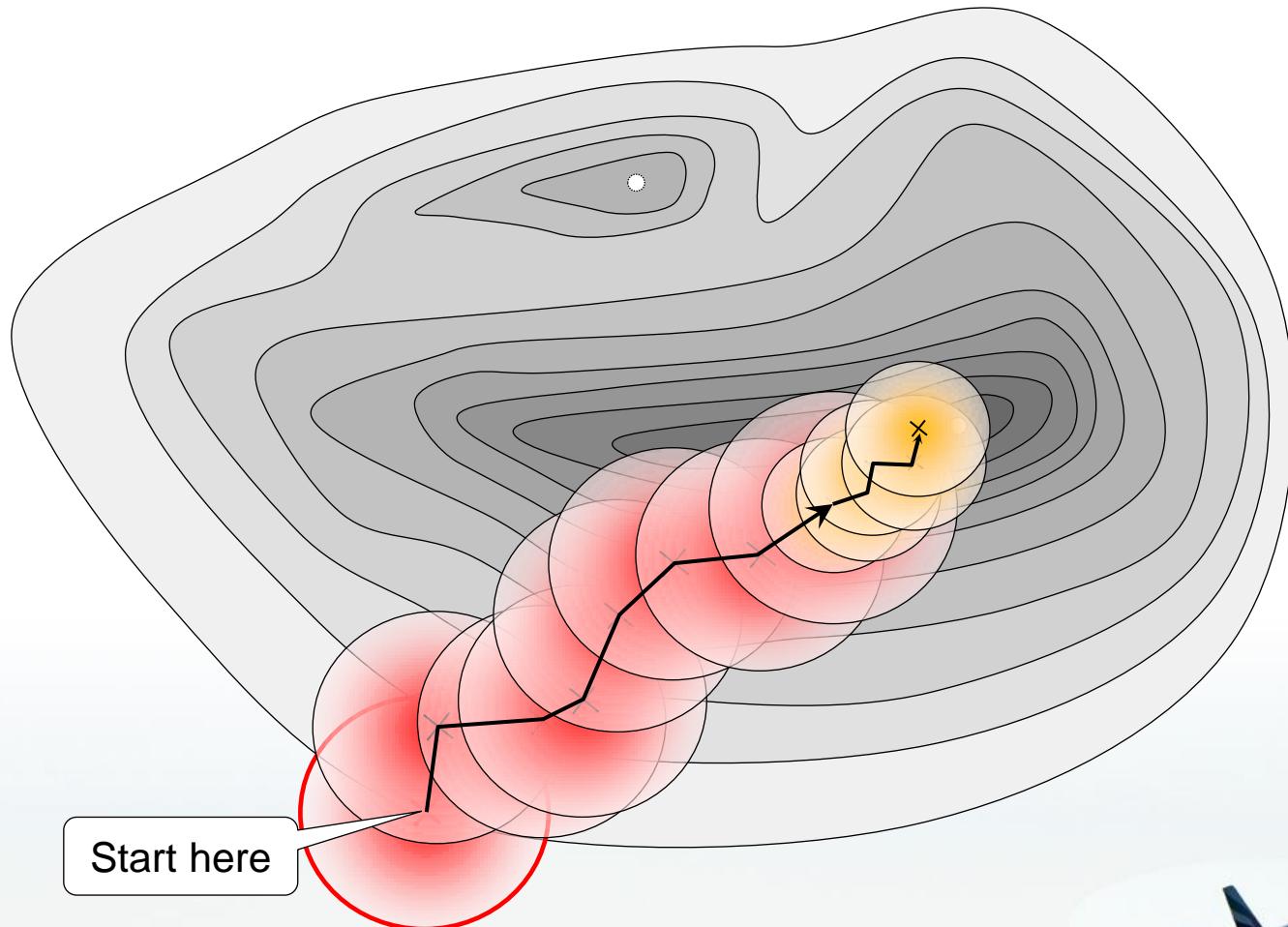
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A Gradient Strategy

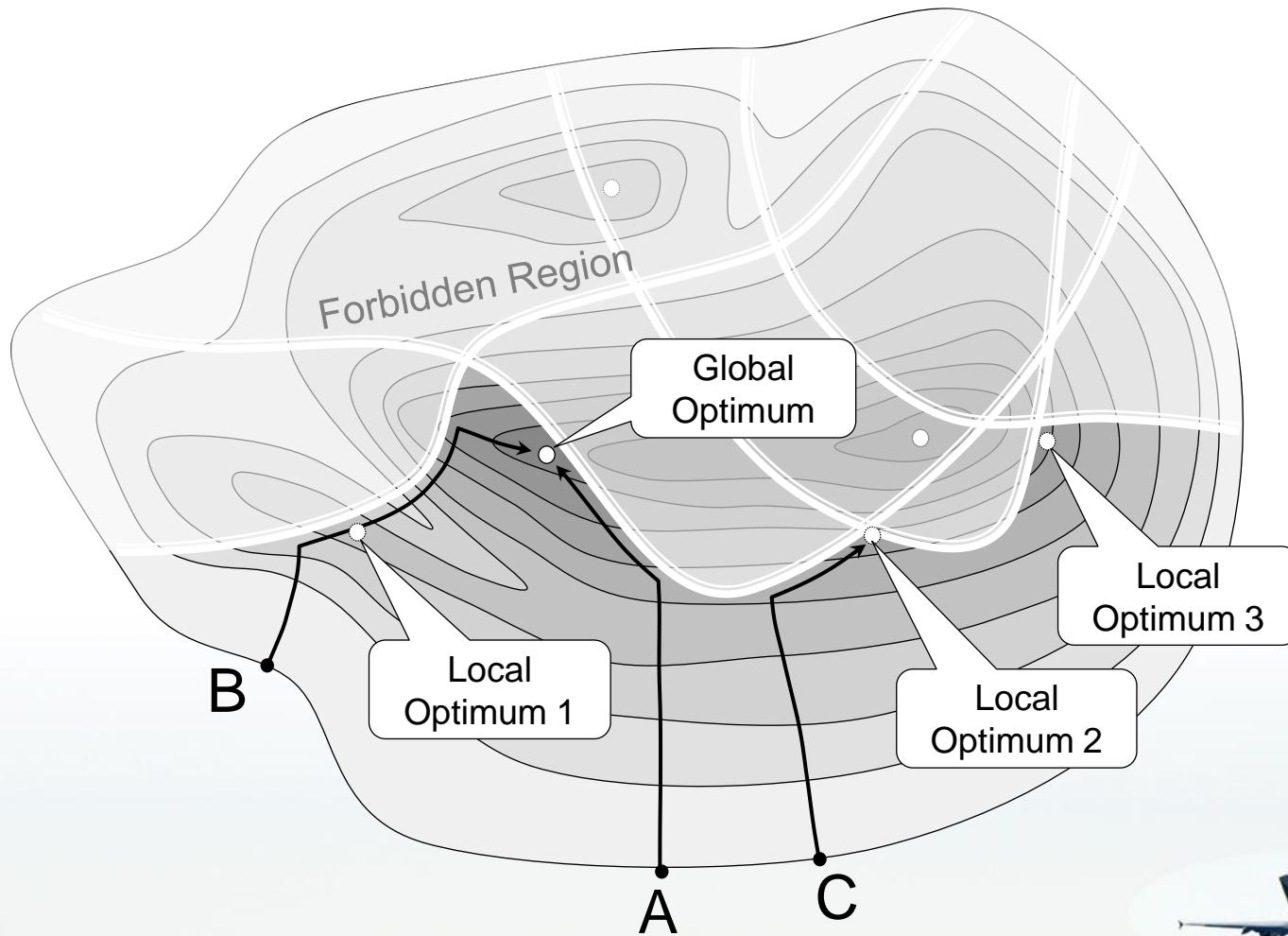


Random Adaptive Search



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Constraints Create Local Optima



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Search for a Valid Starting Point

Maximize Max Climb Thrust

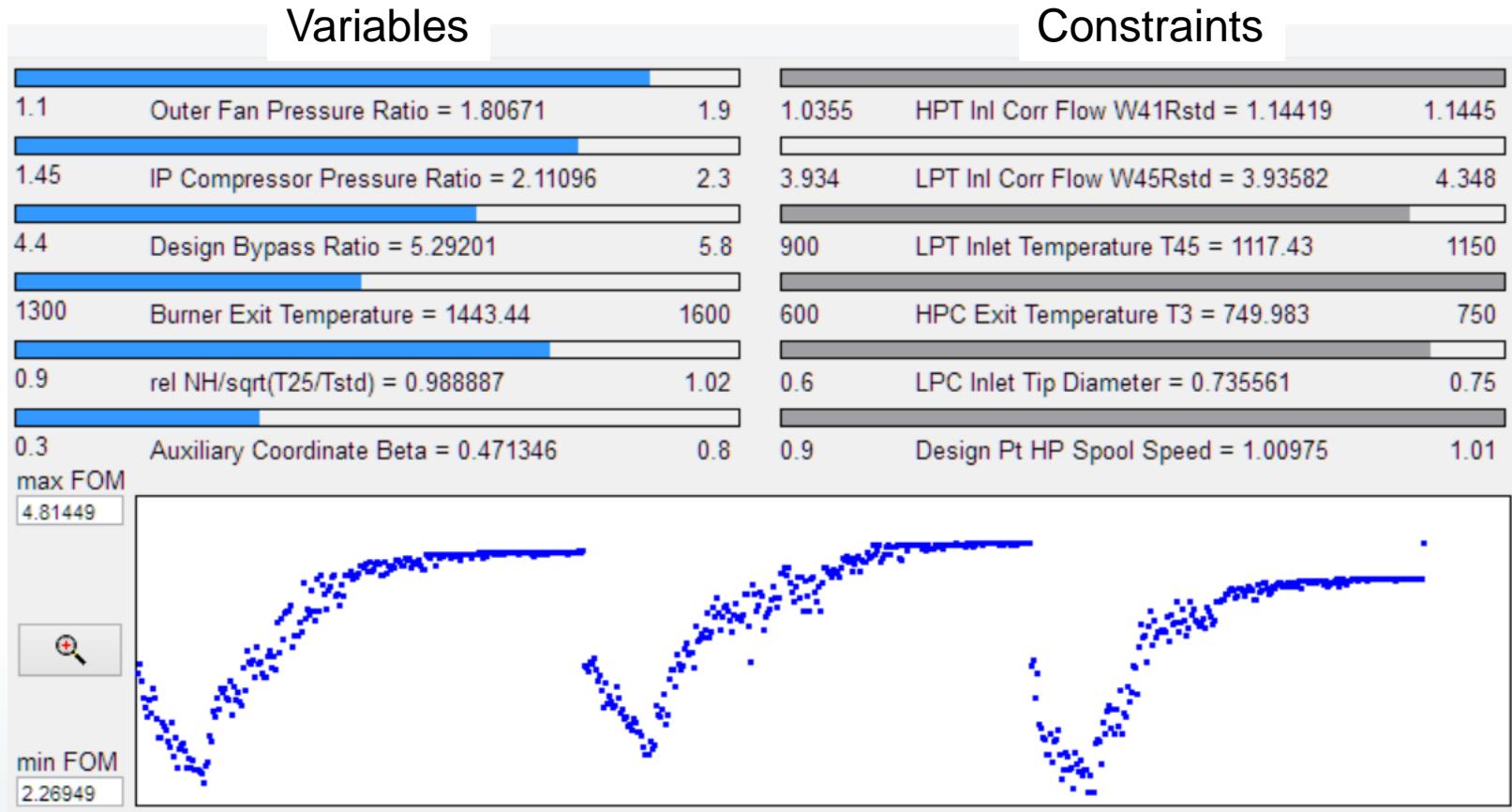


Figure of Merit: Thrust





Minimizing SFC

Variables

1.5	Outer Fan Pressure Ratio = 1.71063	1.9
1.7	IP Compressor Pressure Ratio = 2.11072	2.3
4.5	Design Bypass Ratio = 5.53736	6
1350	Burner Exit Temperature = 1427.34	1550
0.95	rel NH/sqrt(T25/Tstd) = 0.989126	1.02
0.3	Auxiliary Coordinate Beta = 0.465181	0.8

max FOM

19.7604



min FOM

19.3013

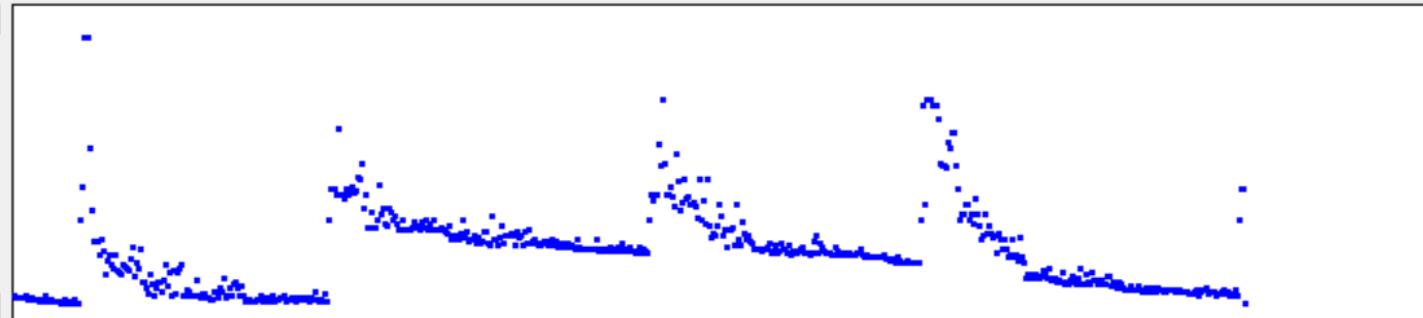


Figure of Merit: SFC





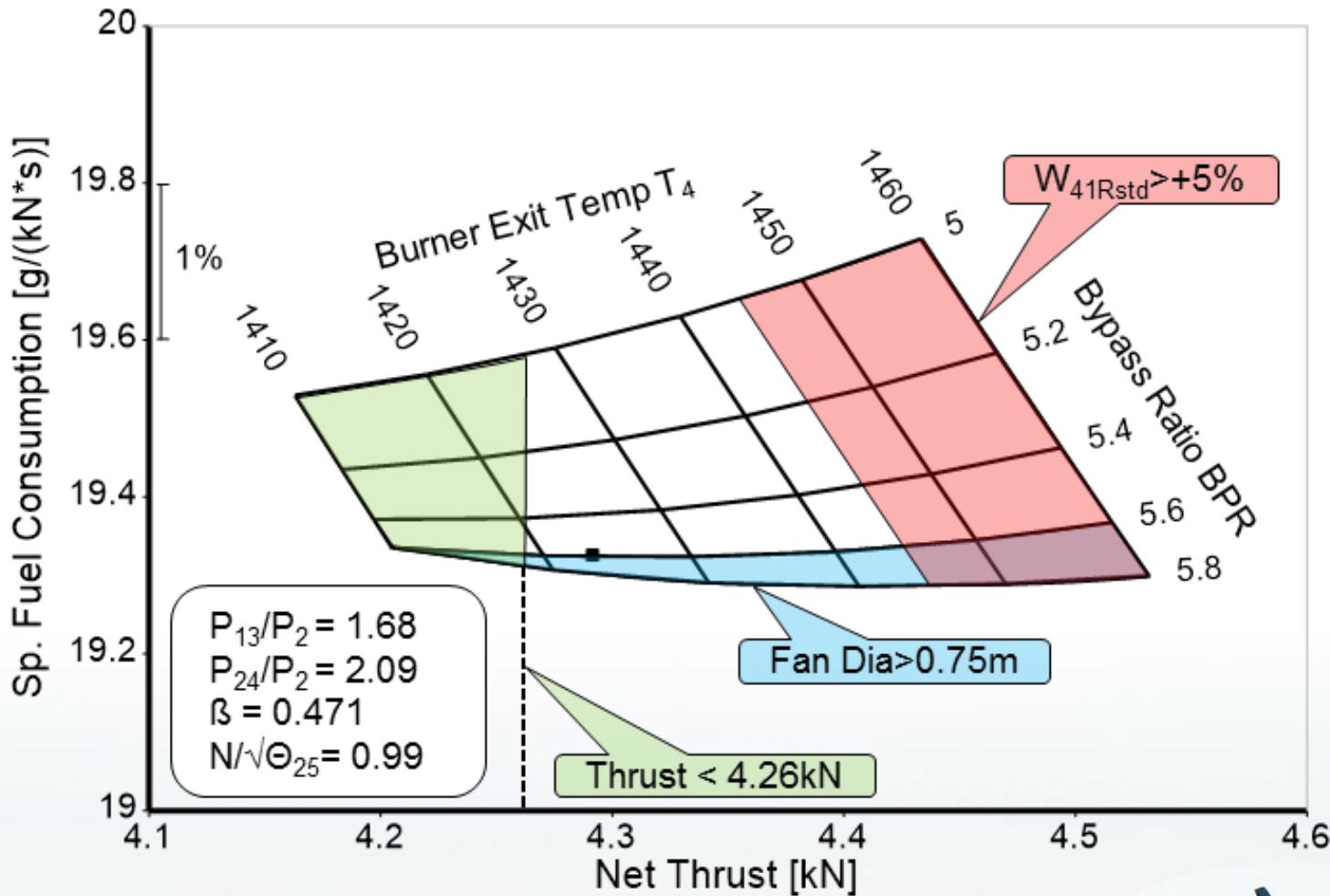
Main Cycle Data

	Baseline Engine		Growth Engine	
	Max Climb	Take Off	Max Climb	Take Off
Thrust [kN]	3.41	12.0	4.29 (+26%)	15.12 (+26%)
SFC [g/(kN*s)]	19.86	13.51	19.33 (-2.7%)	12.78 (-5.4%)
Bypass Ratio	4.5	4.62	5.59	5.77
Fan P_{13}/P_2	1.762	1.573	1.679	1.517
Ideal Jet Vel. Ratio (V_{18}/V_8) _{id}	0.81	0.938	0.737	0.862
Booster P_{24}/P_2	1.85	1.639	2.086	1.828
HPC P_3/P_{25}	12	11.21	11.59	10.72
T_4 [K]	1350	1416	1423	1477
$W_{41\text{Rstd}}$	1.09	1.089	1.135 (+4%)	1.134
$W_{45\text{Rstd}}$	4.141	4.12	3.989 (-3.7%)	3.973
LPT η_{is} (3 Stages)	0.9000	0.9113	0.8806	0.8917
T_3 [K]	647	743	662	750
T_{45} [K]	973	1027	1048	1092
Fan diameter [m]	0.655		0.75	
Core spool speed [rpm]	32000	33600	32320 (+1%)	33936 (+1%)



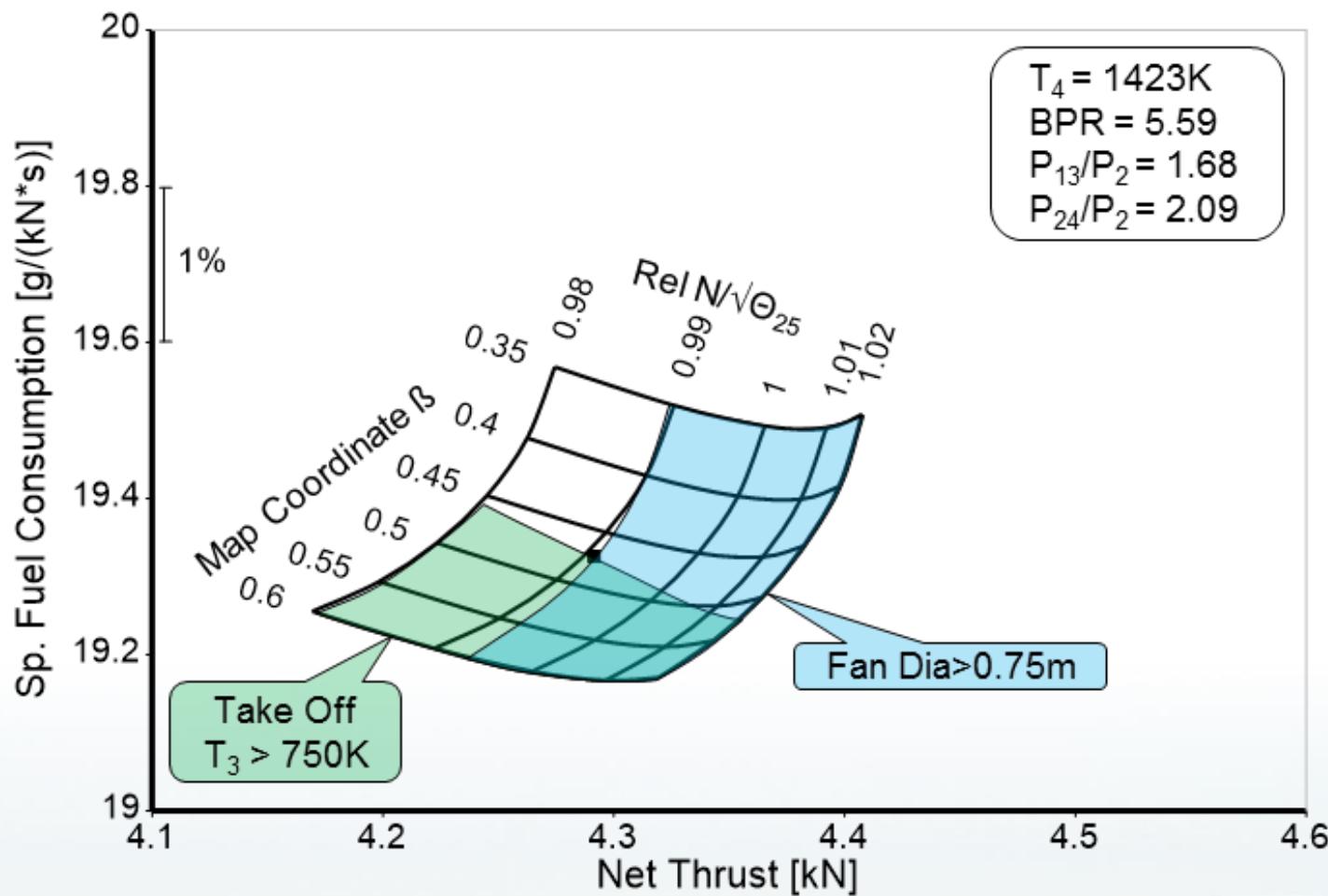


The Design Space (1)



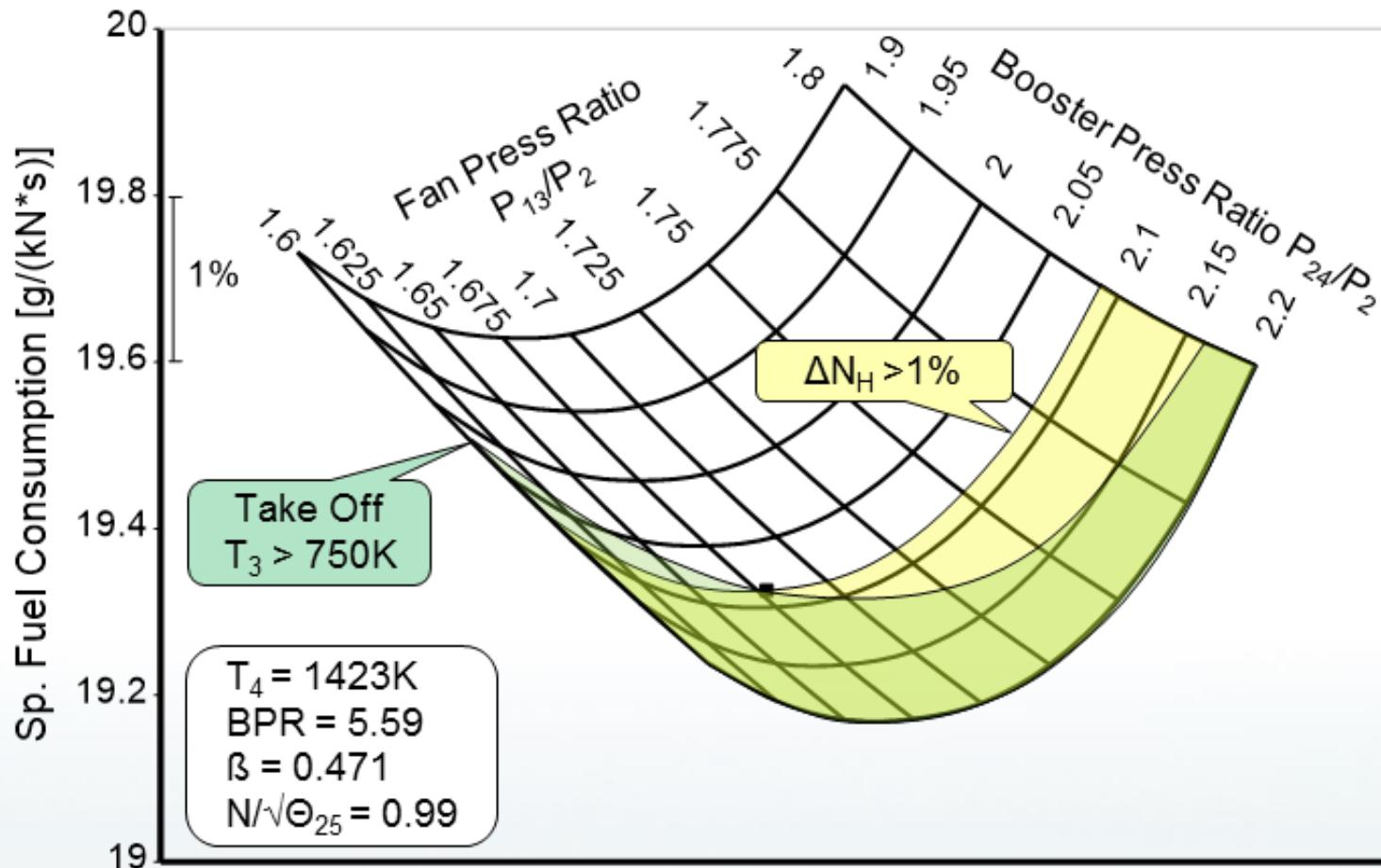


The Design Space (2)





The Design Space (3)



This is Not the End...

- In real life the growth engine optimization would not end after finding a first solution.
 - Specific fuel consumption could be improved even further by adding a fourth stage to the low pressure turbine, for example.
 - An additional special study should also be done to clarify whether the required thrust increase of 25% could be achieved without adding a booster (answer: this is not possible).
 - Another question is "What would the thrust and SFC be if the imposed T_3 limit of 750K at Take Off is replaced by a higher value?"
- Keep always in mind: the optimization algorithm finds only the best solution for the mathematical model.
- The integrity of the result depends on the detail and the quality of the engine model

