Multi-disciplinary System Design Optimisation of a 2-Stage Compressor for Aero-Performance, Production Cost and Dynamic Stability

OUTLINE

INTRODUCTION

- Motivation for integrated design with stability
- Problem definition
- Simulation modules

OPTIMISATION

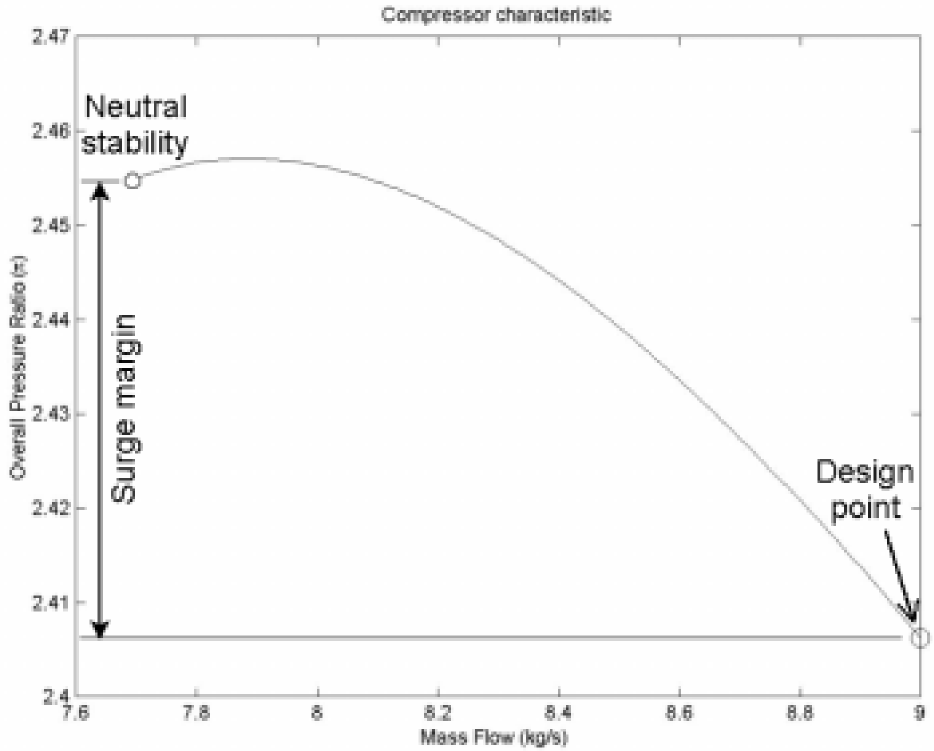
- Initial design space study by DOE
- Single-objective optimisation for Pressure Ratio
- Pareto optimisation for Surge Margin & Cost
- Final multi-objective optimisation

CONCLUSIONS

Motivation for integrated design with stability

- Axial compressor performance measured by:
  - Pressure Ratio – P_{o2}/P_{o1}
  - Adiabatic efficiency – η
- Stability - Surge margin

$$SM = \frac{PR_{NS} - PR_{Design}}{PR_{NS}}$$

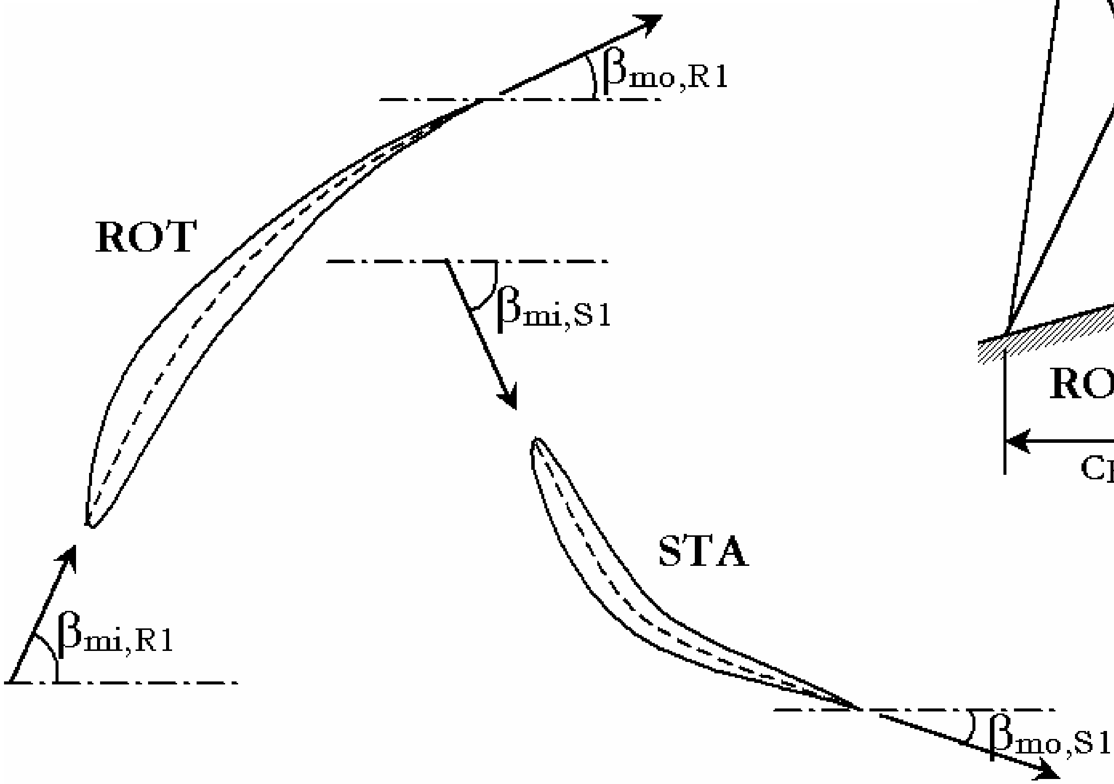


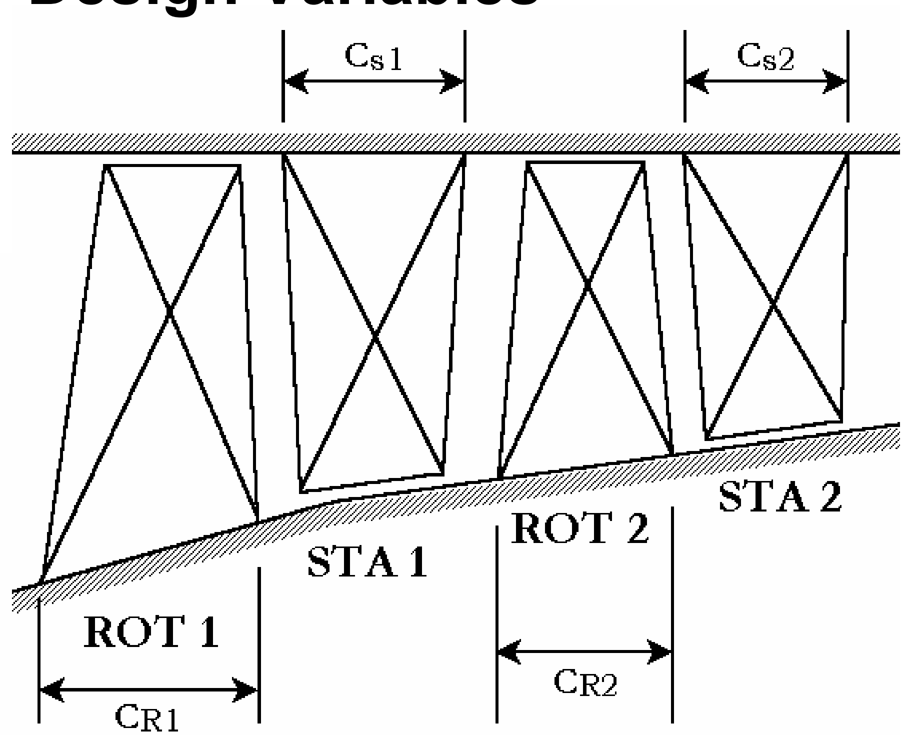
Two main targets

1) Performance optimisation with stability (and cost) accounted for from the start – not usually done
2) Show the potential cost benefits of surge margin reduction

Problem definition – Design Variables

- 8 Design Variables
- Repeating stage geometry





Problem definition – Objectives and constraints

OBJECTIVES

- Maximise Pressure Ratio
- Maximise Efficiency
- Minimise Production Cost (Manufacturing + Material Cost)

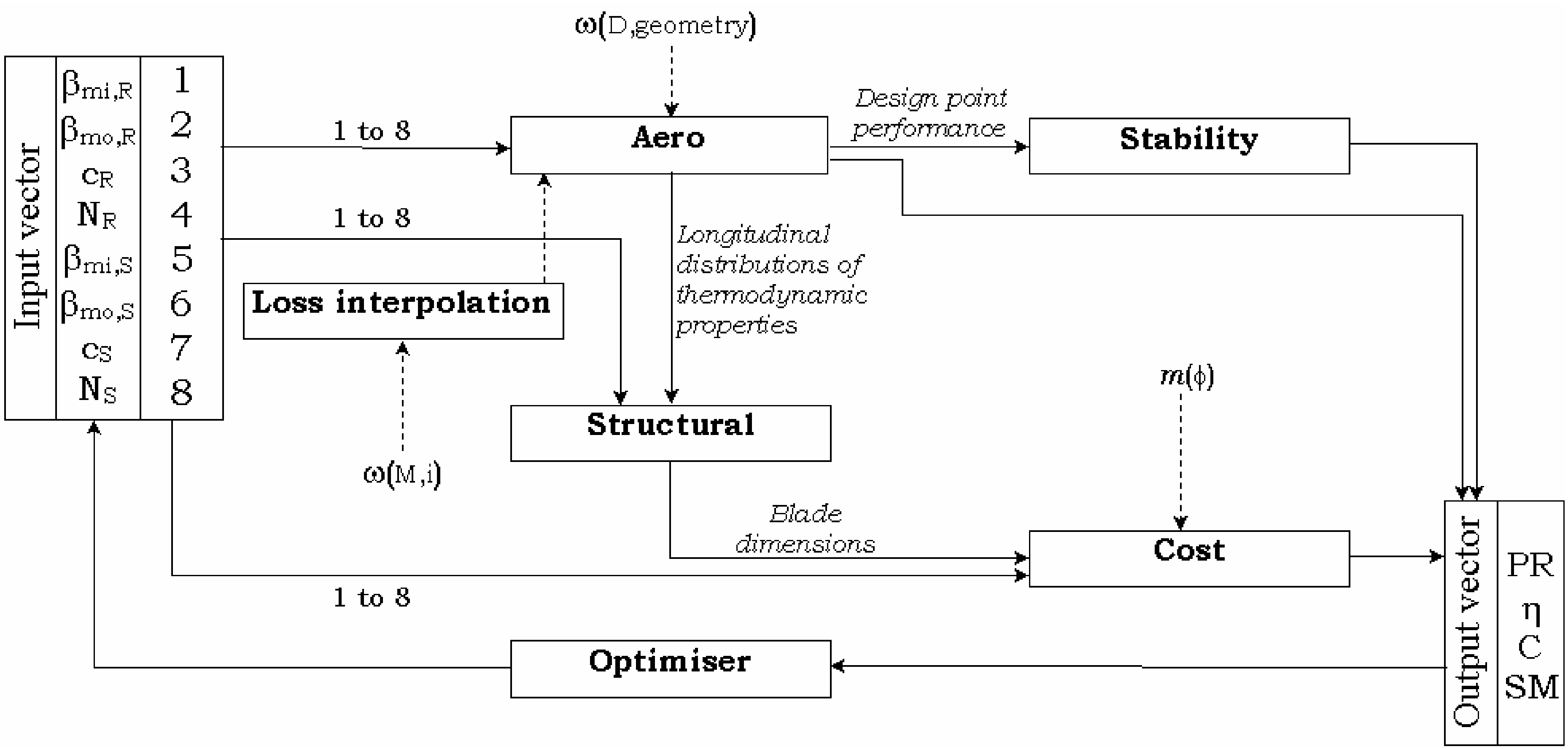
CONSTRAINTS

- Structural integrity – $\sigma_{blades} < \sigma_{ultimate,material}$

** Surge margin treated separately as objective & constraint **

Geometry restricted within bounds known from experience

Simulation architecture



OUTLINE

INTRODUCTION

- Motivation for integrated design with stability
- Problem definition
- Simulation modules

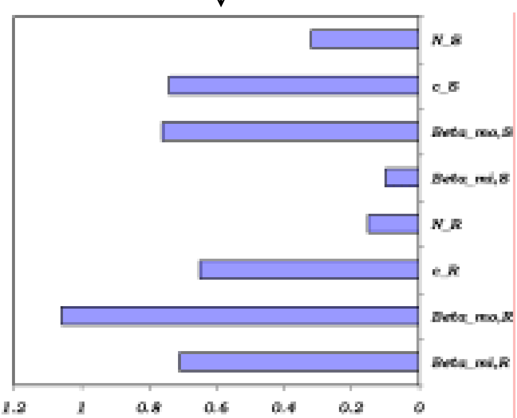
OPTIMISATION

- Initial design space study by DOE
- Single-objective optimisation for Pressure Ratio
- Pareto optimisation for Surge Margin & Cost
- Final multi-objective optimisation

CONCLUSIONS

DOE – Benchmark Point Definition

	Orthogonal Region				Sequenced region			
	A	B	C	D	E	F	G	H
Expt #	$\beta_{mi,R}$	$\beta_{mo,R}$	C_r	N_r	$\beta_{mi,S}$	$\beta_{mo,S}$	C_s	N_s
1	A1	B1	C1	D1	E1	F1	G3	H2
2	A1	B2	C2	D2	E1	F2	G3	H2
3	A1	B3	C3	D3	E2	F3	G1	H3
4	A2	B1	C2	D3	E2	F1	G2	H3
5	A2	B2	C3	D1	E3	F1	G3	H1
6	A2	B3	C1	D2	E3	F2	G1	H2
7	A3	B1	C3	D2	E1	F2	G1	H3
8	A3	B2	C1	D3	E2	F3	G2	H1
9	A3	B3	C2	D1	E3	F3	G2	H1



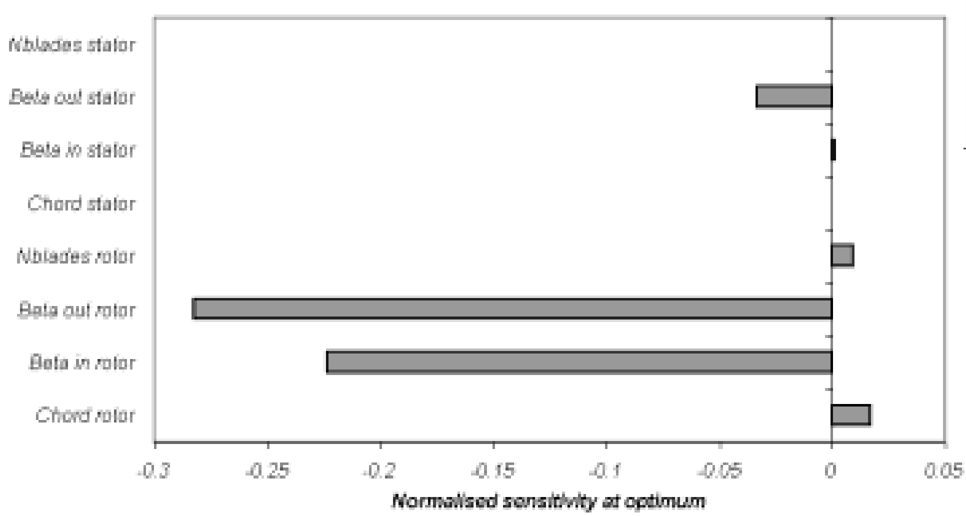
Symbol	Level	Effect	Value
$\beta_{mi,R}$	A2	0.71	63
$\beta_{mo,R}$	B1	1.06	33
c_R	C1	0.65	0.06
N_R	D1	0.15	67
$\beta_{mi,S}$	E3	0.10	62
$\beta_{mo,S}$	F1	0.76	8.66
c_S	G2	0.74	0.08
N_S	H1	0.32	65

- Generation of initial point for numerical optimisation
- "Quasi-orthogonal" array
- Cumulative weighted effects calculated
- Highest effects from exit metal angles – especially rotor
- Chord effects also important – they mainly affect stability

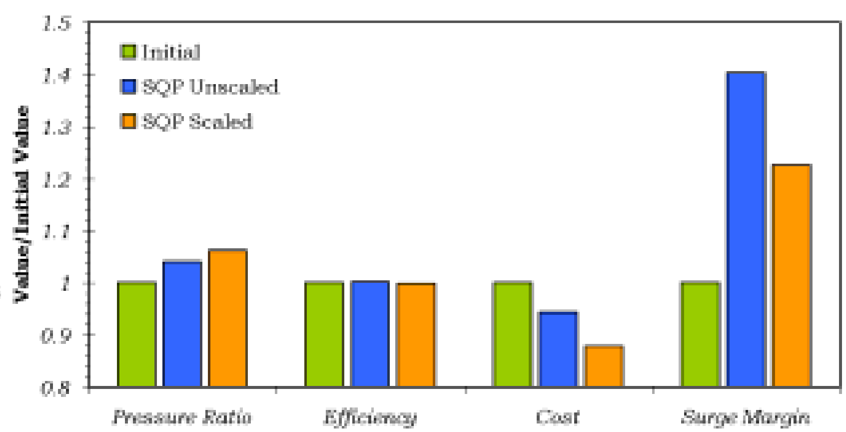
Single-Objective Gradient-Based Optimisation (SQP)

- Select Pressure Ratio as objective – find the performance ceiling
- Sensitivity analysis based on this first optimisation – angles dominant
- Scaling: $\beta_{in,rotor}$ (*x 0.01*), $\beta_{out,rotor}$ (*x 0.01*), $\beta_{in,stator}$ (*x 0.01*)

Nondimensional pressure ratio sensitivity w.r.t. each variable.



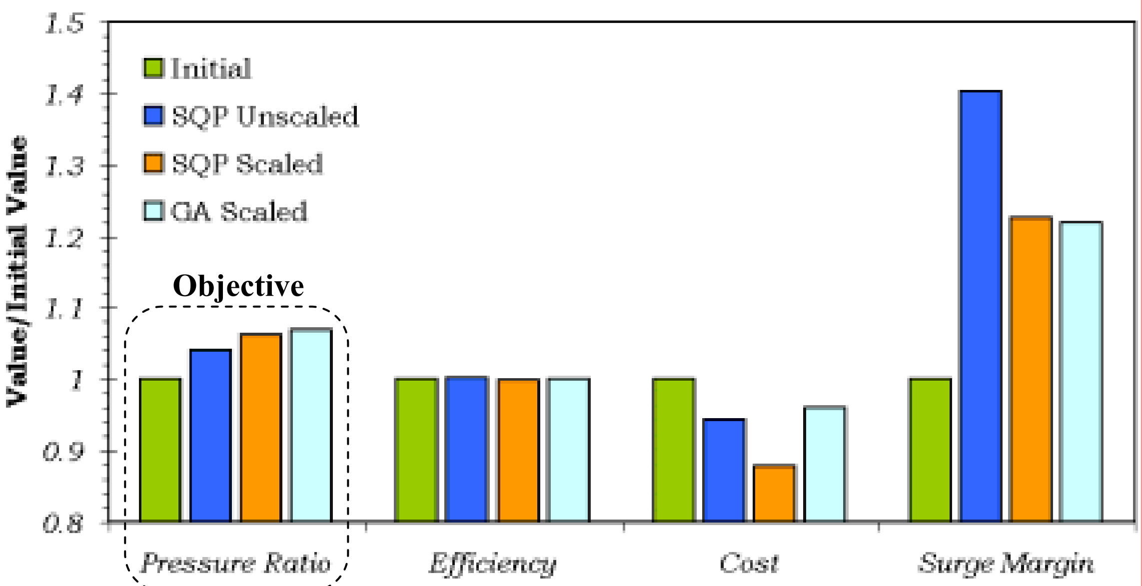
Design variable	Initial values	SQP before scaling	SQP after scaling
PR	2.317	2.412	2.463
η	0.976	0.978	0.975
Cost	191.095	180.38	167.737
SM	0.164	0.230	0.201



Single-Objective Heuristic Optimisation (GA)

- Parametric study of the GA tuning parameters
  - <u>Mutation rate</u>: 0.04 – Optimum convergence speed
  - <u>Population size</u>: 40 – Higher than this brings overall fitness down
  - <u>Generations</u>: 40 – Limited by time constraints

*** Better to use up iterations in more generations than more individuals ***



- Improvement over previous best scaled-SQP design
- *SQP design was a local optimum – very nonlinear space*

Pressure Ratio performance ceiling established

OUTLINE

INTRODUCTION

- Motivation for integrated design with stability
- Problem definition
- Simulation modules

OPTIMISATION

- Initial design space study by DOE
- Single-objective optimisation for Pressure Ratio
- Pareto optimisation for Surge Margin & Cost
- Final multi-objective optimisation

CONCLUSIONS

Pareto Optimisation for Surge Margin and Cost

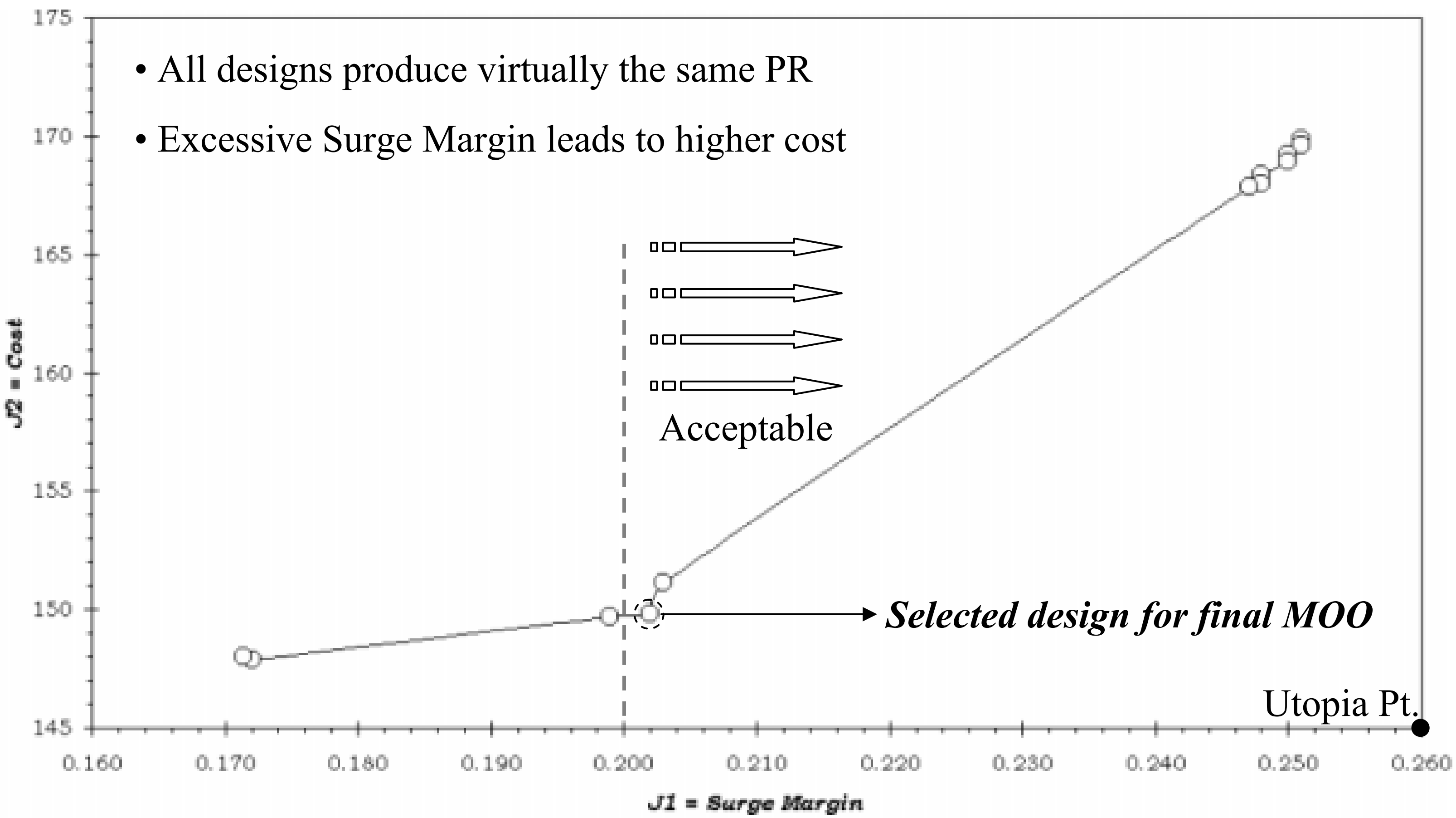
- Pressure Ratio set at acceptable limit based on SOO results (PR > 2.4)
- Efficiency seen to not vary substantially
- Cost and Surge Margin opposing:
  - *Lower cost >> Smaller, lower number of blades*
  - *Higher stability >> Larger, higher number of blades*

- Weighted function approach towards generation of the Pareto Front

$$J = \lambda\left(\frac{SM}{SM_o}\right) + (1-\lambda)\left(\frac{C}{C_o}\right)$$

- SQP used to minimise this objective.

Pareto Front



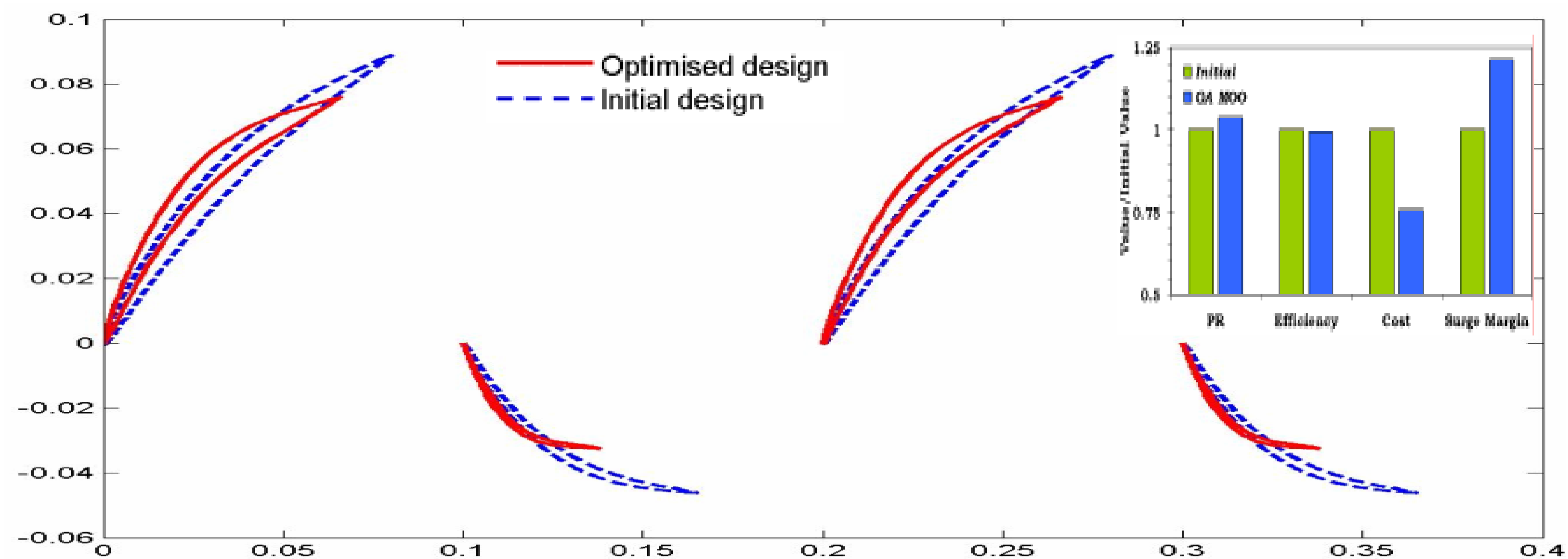
Final Multi-Objective Optimisation (GA)

• Attempt further improvement on Pareto solution

• Now in a very confined region of the design space – small performance variations expected

•Probably global optimum – same solution after 2000+ iterations

		After DOE	MOO	
		Initial values	GA MOO	
PR	⇧	2.317	2.406	+4%
η	⇧	0.976	0.972	-0.41%
C	⇩	191.095	144.515	-24.4%
SM (>20%)		0.164	0.199	+22%



Conclusions

- An integrated design philosophy is possible and successful
    - SOO gives a measure of the maximum machine performance
    - Pareto bi-objective approach determines the cost-stability relation
    - Final MOO produces the fully optimised solution

- Surge margin places a very hard constraint on the cost of optimal-performance machines – very conservative. Reduction in Surge Margin promises very significant Cost Savings.

Questions ?