



## **On board adaptive models: A general framework and implementation aspects**

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**On board adaptive models:**  
**A general framework and implementation aspects**

§Structure of adaptive models

§Adaptive model of a partially mixed turbofan

§Implementation aspects

§Diagnostic effectiveness and timing investigations

§Discussion

§Conclusions



## Why Adaptive models?

F Individual engines of a particular model are not identical

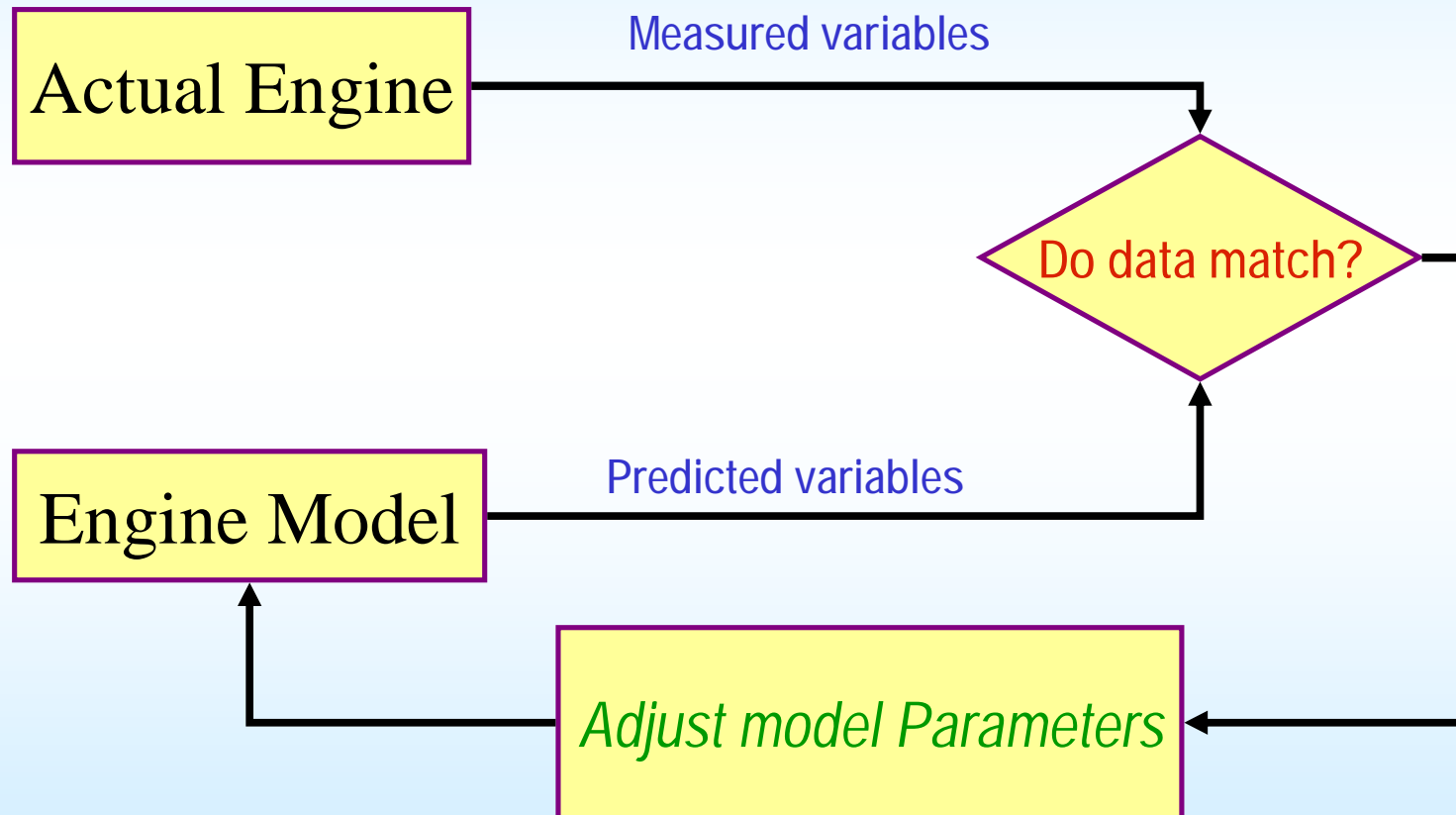
F One particular engine alters with time (aging, deterioration)

F Engines §suffer from faults,  
§are repaired,  
§are overhauled

**Desire to represent the performance of an individual engine as accurately as possible in all situations**



## The principle of Adaptive models





## Structure of Adaptive models

### Modification factors $f_k$ for components

$x_{p,k}$  : Actual value for parameter

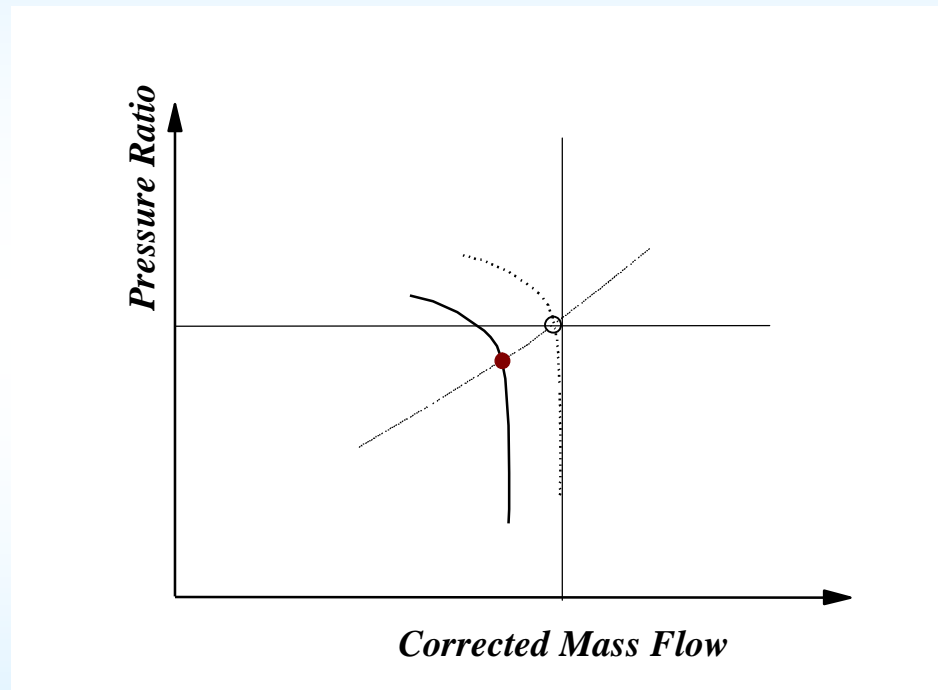
$x_{p,ref,k}$  : Reference value for parameter

$$f_k = \frac{x_{p,k}}{x_{p,ref,k}}$$

### Transformation of component performance maps



## The meaning of Modification factors

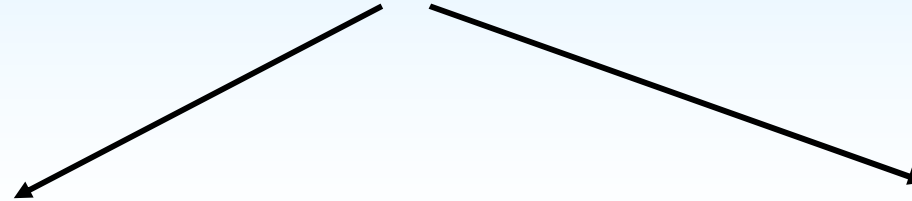


## Transformation of component performance maps



## Implementation aspects

### Adaptation



### External

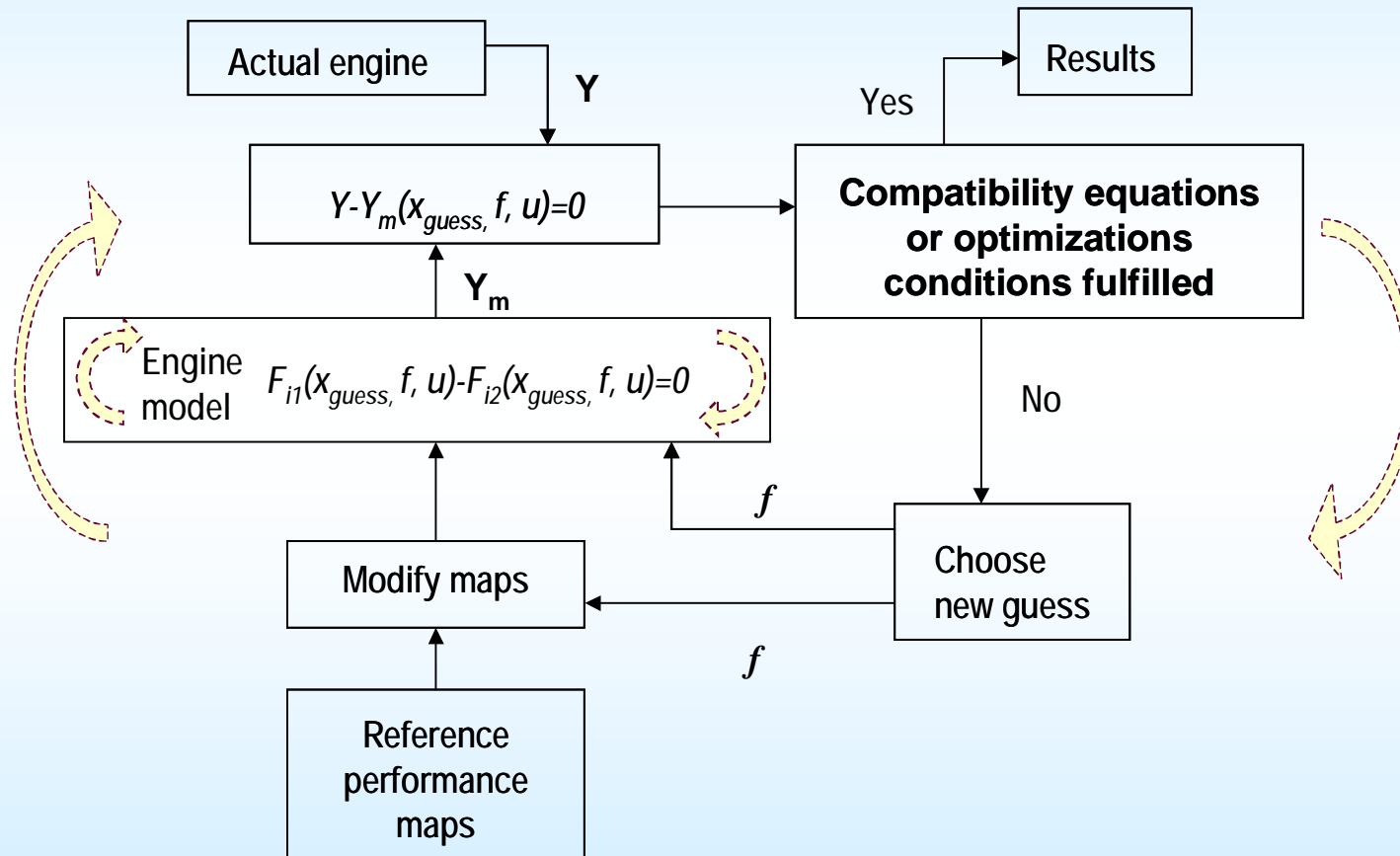
Separate solution for error  
and adaptation equations

### Internal

Concurrent solution of error  
equations  $F_i(\cdot) = 0$  and adaptation  $Y-$   
 $Y_m(\cdot) = 0$



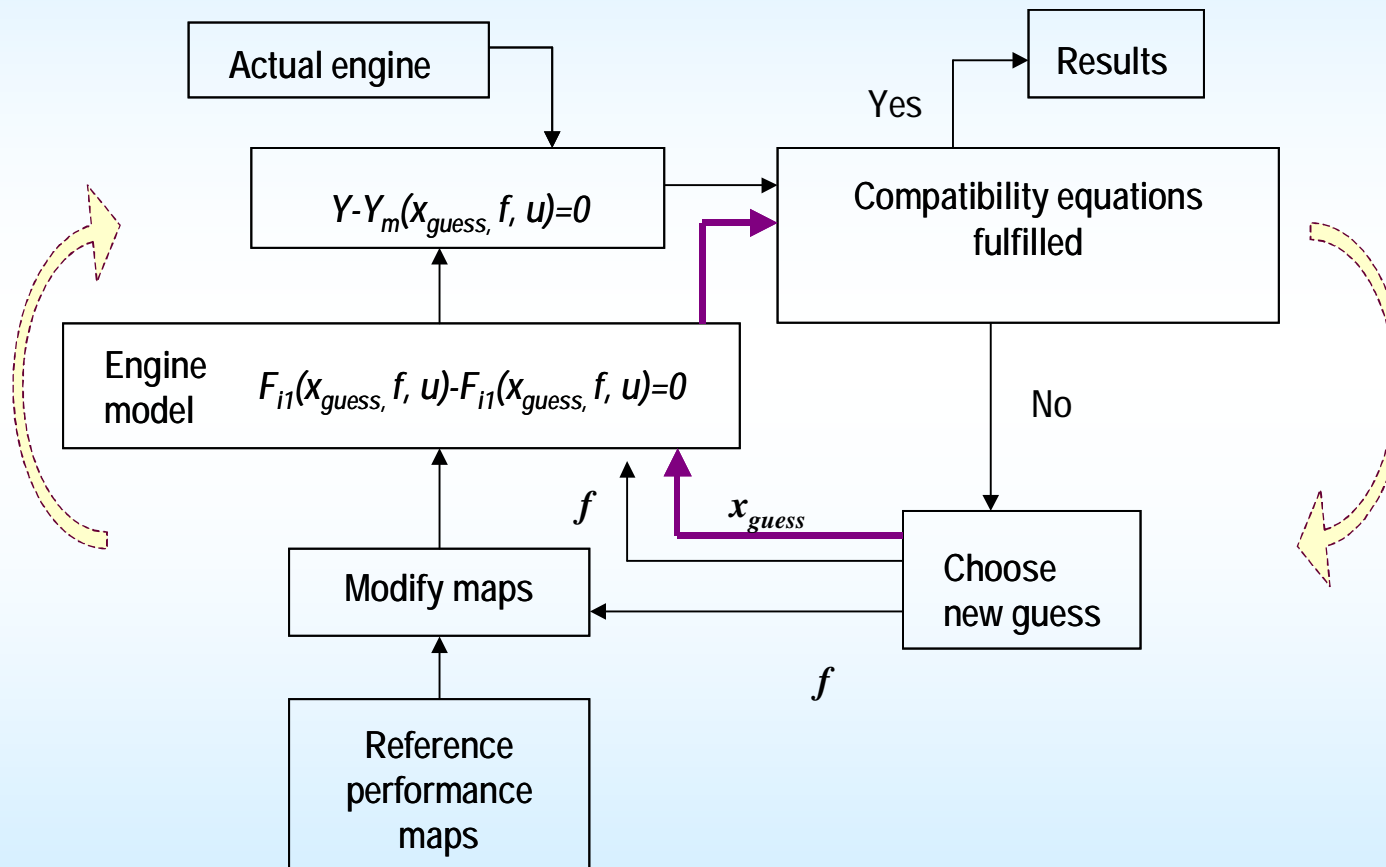
## External Adaptation







## Internal Adaptation





## Turbofan adaptive model presentation

### Input parameters

§Quantities defining the operating condition (  $u$  vector )

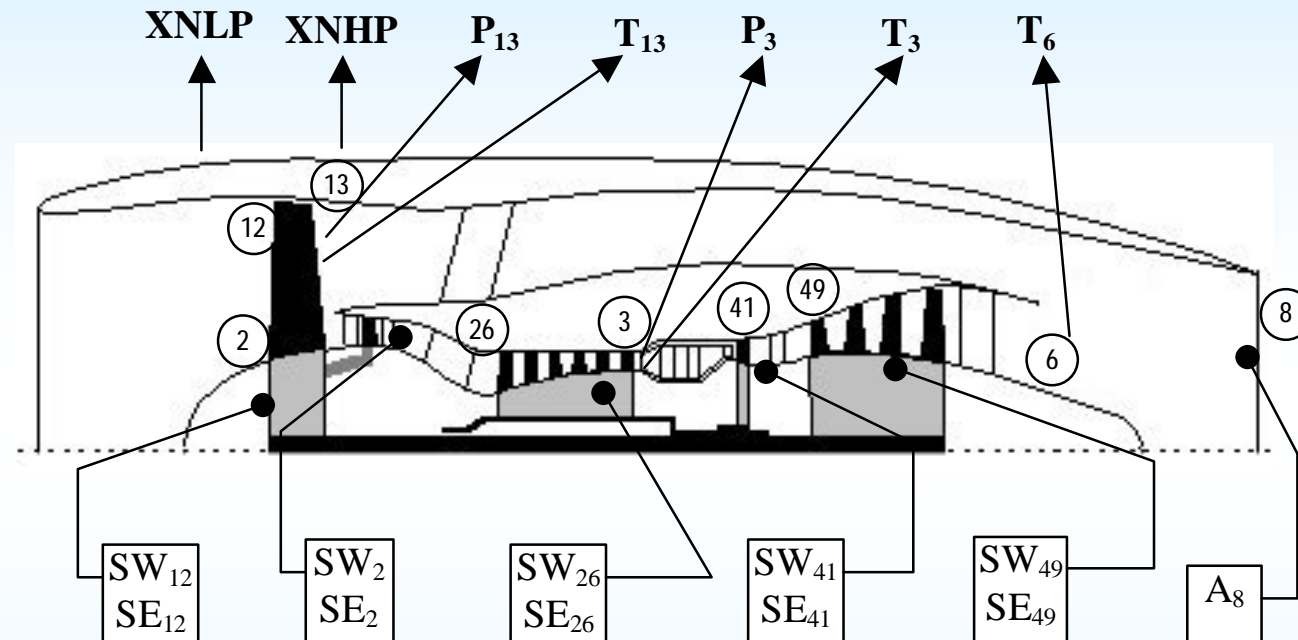
§Quantities expressing the condition of individual components (  $f$  vector )

### Output parameters

§Quantities expressing the measured variables from the engine (  $Y$  vector )



## Station numbering and definitions



$$SW_i = \frac{W_i \cdot \sqrt{T_i}}{p_i} / \left( \frac{W_i \cdot \sqrt{T_i}}{p_i} \right)_{ref}$$

$$SE_i = \frac{\eta_i}{(\eta_i)_{ref}}$$

$$A8_{IMP} = \frac{A8}{A8_{ref}}$$



## Typical Monitoring Sets

### Measurements

	Measurements for Monitoring	Symbol
1	LP Shaft Rpm	XNLP
2	HP Shaft Rpm	XNHP
3	Fan Outer Pressure	$P_{13}$
4	HP Compressor Outlet Pressure	$P_3$
5	HP Compressor Outlet Temperature	$T_3$
6	LP Turbine Outlet Temperature	$T_6$
7	Fan Outer Temperature	$T_{13}$
	<b>Operation Point Definition</b>	
1	Ambient Pressure	Pamb
2	Total Inlet Pressure	$P_1$
3	Total Inlet Temperature	$T_1$
4	Fuel Flow Rate	WFE

### Component Condition Parameters

Component	Health Parameter	Symbol	No
Outer Fan	Flow Factor	SW12	1
	Efficiency Factor	SE12	2
Fan Inner	Flow Factor	SW2	3
	Efficiency Factor	SE2	4
HPC	Flow Factor	SW26	5
	Efficiency Factor	SE26	6
HPT	Flow Factor	SW41	7
	Efficiency Factor	SE41	8
LPT	Flow Factor	SW49	9
	Efficiency Factor	SE49	10
Nozzle	Exhaust Area	A8IMP	11



## Diagnostic effectiveness and timing investigations

### Sample Test Cases Examined

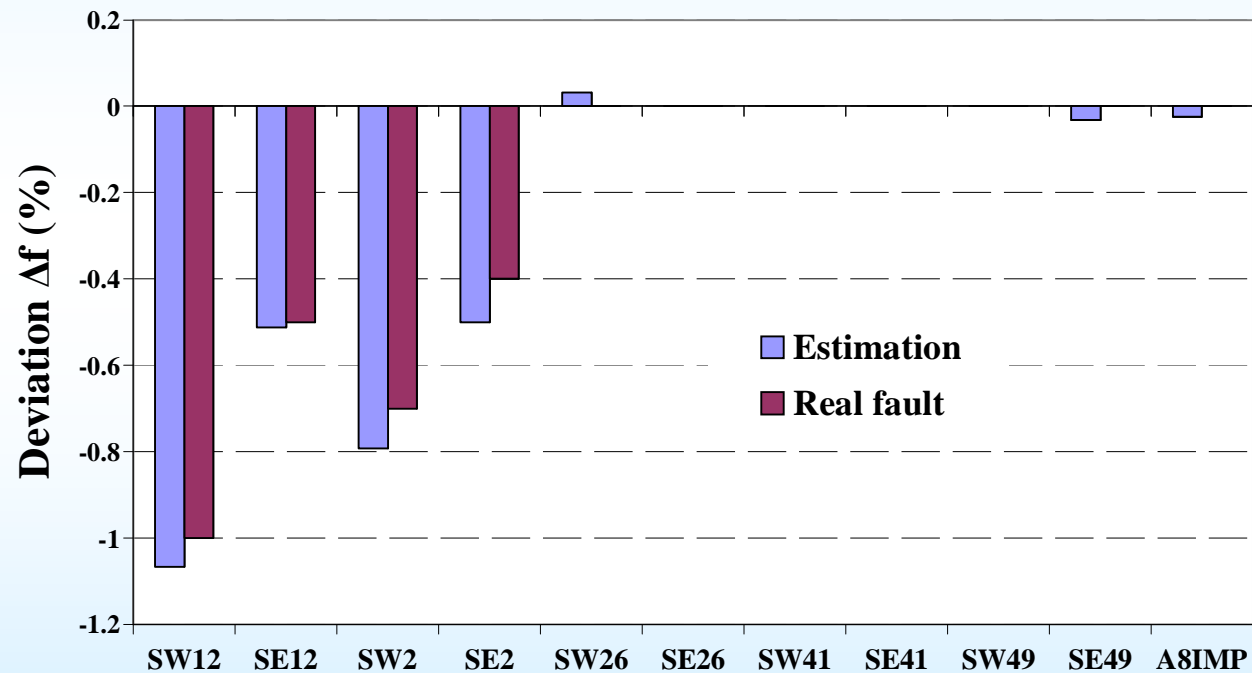
1. Internal adaptation 7x7 Solver: Newton type (inclusive)
2. Internal adaptation 7x7 Solver: Newton type, (non inclusive)
3. Internal adaptation 11x11 Solver: Newton type
4. External adaptation 7x7 Solver: Newton type
5. External adaptation 7x7 Solver: Hill Climbing
6. External adaptation 7x11 Solver: Hill Climbing



## Diagnostic effectiveness and timing investigations

Solver: Newton type  
Adaptation: Internal 7x7

Test Case 1



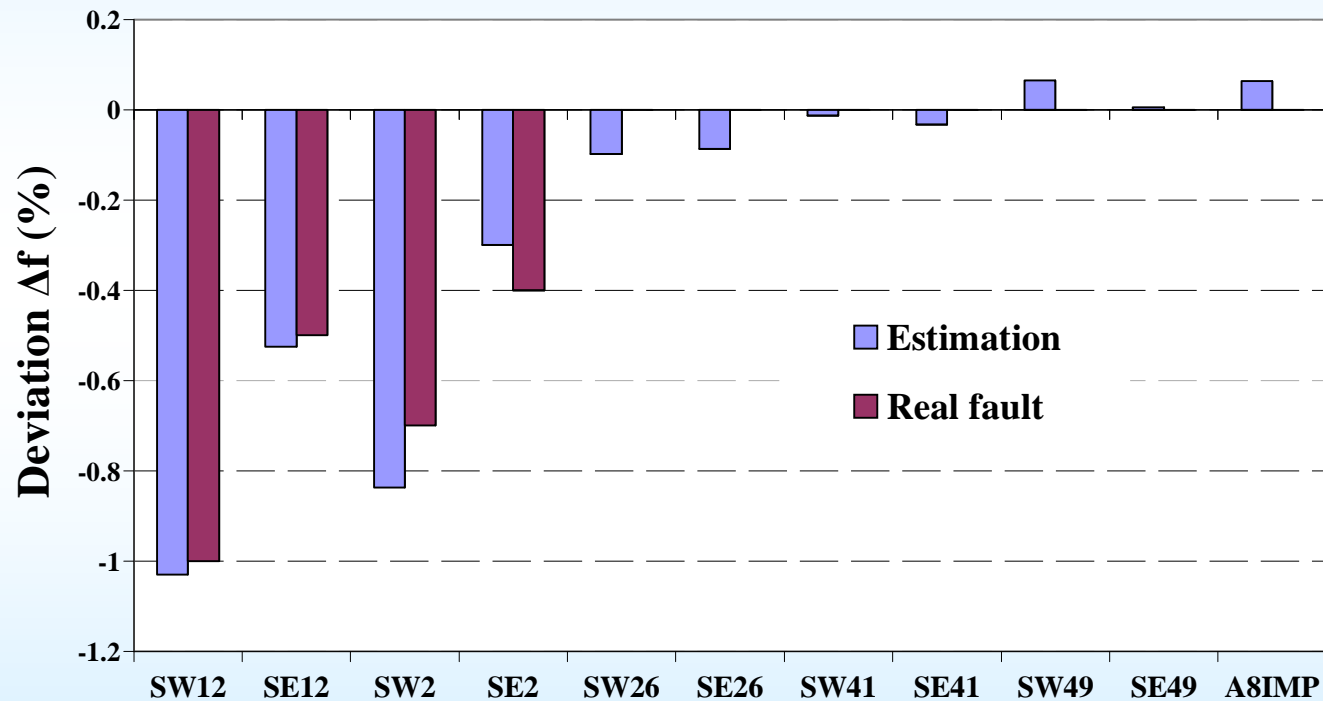
Adaptation time equal to 1x Simulation Time



## Diagnostic effectiveness and timing investigations

Test Case 6

Solver: Hill Climbing  
Adaptation: External 7x11



Adaptation time equal to 400 x Simulation Time



## Diagnostic effectiveness and timing investigations

	Test Case	Needed Time
1	Internal adaptation 7x7 Solver: Newton type	Ts
2	•Internal adaptation 7x7 Solver: Newton type combination does not contain fault	Ts
3	•Internal adaptation 11x11 Solver: Newton type	Ts
4	•External adaptation 7x7 Solver: Newton type	20 Ts
5	•External adaptation 7x7 Solver: Hill Climbing	100 Ts
6	•External adaptation 7x11 Solver: Hill Climbing	400 Ts

*Ts: Time for simulation run (<<real time)*





## **Aspects of Adaptive Modeling Implementation**

- Effect of fixed number for iterations
- Forms of tested objective functions
- Effectiveness of numerical methods
- Features of adaptive models
- Turbofan engine simulator software

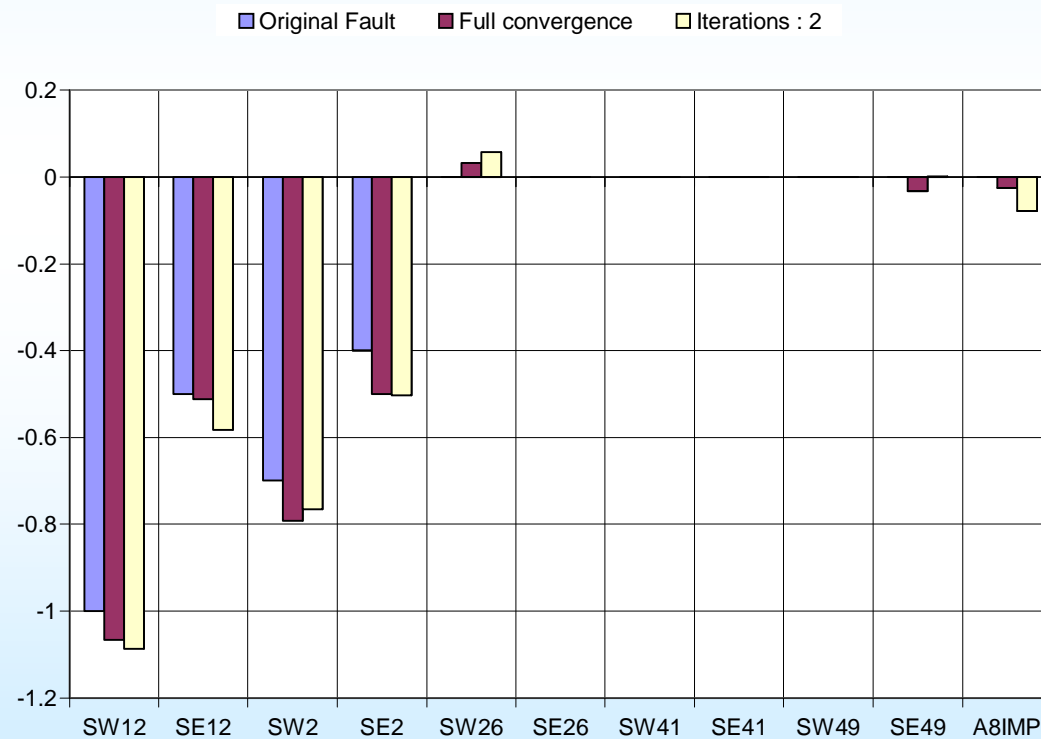


## Effect of fixed iterations

### Solution algorithm: Newton type

Effect of fixed number of iterations  
to estimation

Internal adaptation, 7x7





## Forms of tested objective functions

$$OF_1 = \sum_{i=1}^7 \left[ \frac{Y_i - Y_{m,i}(u, f)}{Y_i S_{y,i}} \right]^2$$

$$OF_2 = \sum_{i=1}^7 \left[ \frac{Y_i - Y_{m,i}(u, f)}{Y_i S_{y,i}} \right]^2 + \sum_{j=1}^{11} \left[ \frac{f_j - f_{ref,j}}{f_{ref,j} S_{f,j}} \right]^2$$

$$OF_3 = \sum_{i=1}^7 \left[ \frac{Y_i - Y_{m,i}(u, f)}{Y_i S_{y,i}} \right]^2 + \sum_{j=1}^{11} \left| \frac{f_j - f_{ref,j}}{f_{ref,j} S_{f,j}} \right|$$



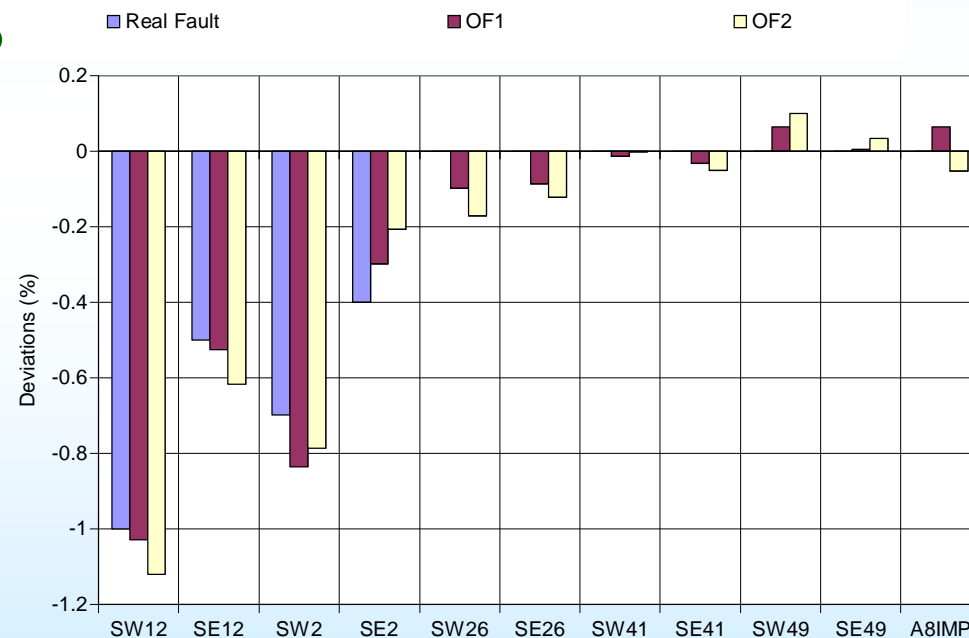
## Test of several forms of objective functions

### Test Case: Fault

Solution algorithm: Hill Climbing

Effect of objective function to estimation. Case: Fault

External adaptation, 7x11





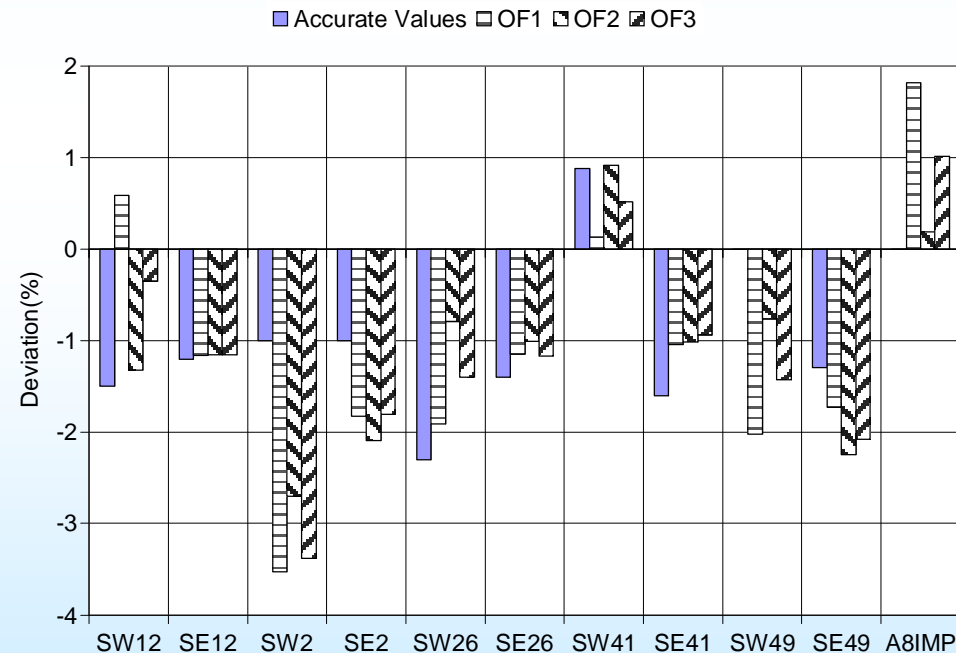
## Test of several forms of objective functions

### Test Case: Deterioration

**Solution algorithm: Hill Climbing**

Effect of objective function to estimation. Case: Deterioration

External adaptation, 7x11



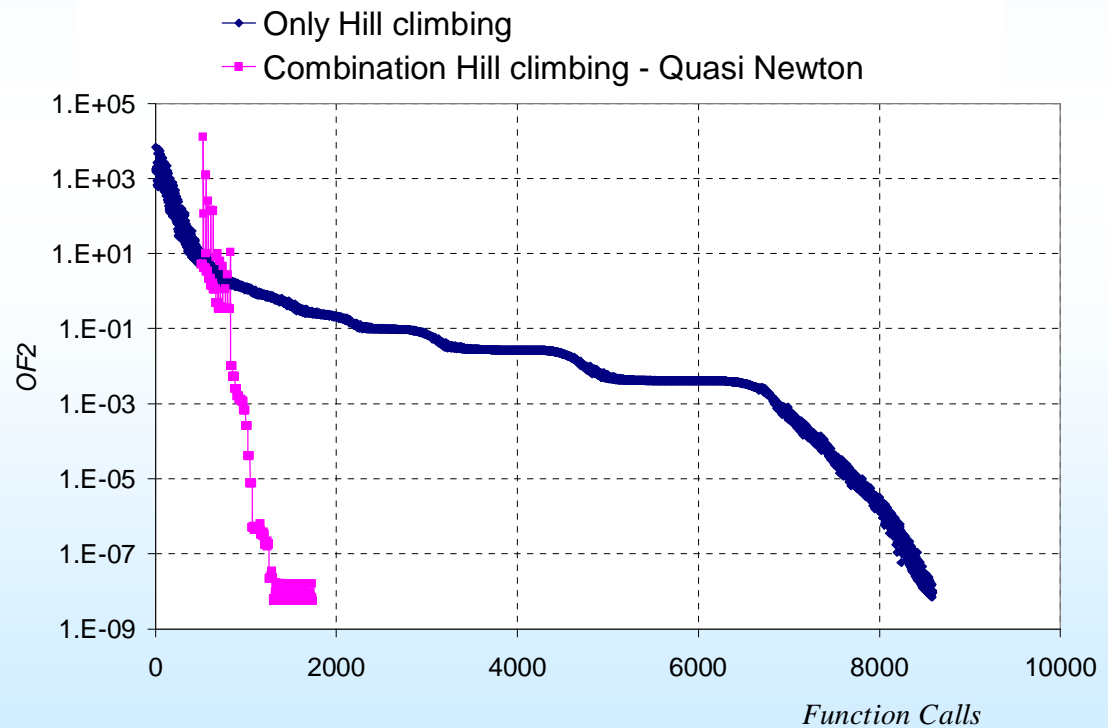


## Effectiveness of numerical methods

### Hill climbing versus Quasi-Newton

Case: Fault

External adaptation,  $7 \times 11$





## **Features of Adaptive Models**

- Using powerful microprocessors it is feasible to adapt an engine model in a time scale which varies between fraction of real time to few seconds (with current microprocessors)
- Real time adaptation offers the possibility of improved control capability
- The described procedures can be implemented in a software package in a user friendly environment



## Turbofan engine simulator software

**TurboFan Engine Simulator - [Performance Calculator]**

Input Measurements Graphs Settings Results Stop Exit Help

**Operating Conditions**

Operating Range

Flight Altitude (m): 0  
Amb. Temp. Diff. from ISA (C): 0  
Flight Mach Number: 0  
Ram Pressure Recovery: 0.99  
NL (rpm): 2000-4000

**Performance Parameters**

NH (rpm)	10103-12271	EPR	1.049-1.368
P13 (bar)	1.114-1.584	T13 (C)	25-59.3
P26 (bar)	1.229-2.258	P42 (bar)	1.802-5.492
T26 (C)	35.5-100.4	T42 (C)	429.2-797.5
P3 (bar)	7.67-24.945	P5 (bar)	1.063-1.393
T3 (C)	293.6-509.8	T41 (C)	685.9-1178.3
T6 (C)	337.1-495.7	Thrust (N)	21212-115478
		W/F (Kg/s)	0.228-1.125

**Health Condition Parameters**

Fan Out Flow Drop (f1)	0	HPT Eff. Drop (f8)	0
Fan Out Eff. Drop (f2)	0	LPT Flow Drop (f9)	0
Fan In Flow Drop (f3)	0	LPT Eff. Drop (f10)	0
Fan In Eff. Drop (f4)	0	Nozzle Area Change (f11)	0
HPC Flow Drop (f5)	0		
HPC Eff. Drop (f6)	0		
HPT Flow Drop (f7)	0		

**Case Identifier**  
Unidentified  
Run

**Simulation**  
 Simulation  
 Diagnosis

**3D Engine Model**

Thrust=21212-115478 Nt  
TSFC=0.034-0.039 Kg/Nt/hr

**Select Engine Type:**  
TurboFan Engine

**Graph: Pressure Ratio vs Mass Flow Cor.**

Mass Flow Cor.	Pressure Ratio
1.6	1.6
2.7	4.1
3.8	6.6
4.9	9.1
6.0	11.6
7.1	14.1
8.2	16.6

HPC | Fan Out | Fan In | Diagnostic Indices | Performance Param.

Demo available at [www.ltt.ntua.gr](http://www.ltt.ntua.gr)





## **Conclusions**

- Real time capability of adaptive performance model has been proven
- Using appropriate formulation it is possible to estimate the engine condition even if limited information is available
- The ability of adaptive performance model to adapt itself to engine condition permits the use of such models as on board observers