On board adaptive models:
A general framework and implementation aspects

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On board adaptive models: A general framework and implementation aspects

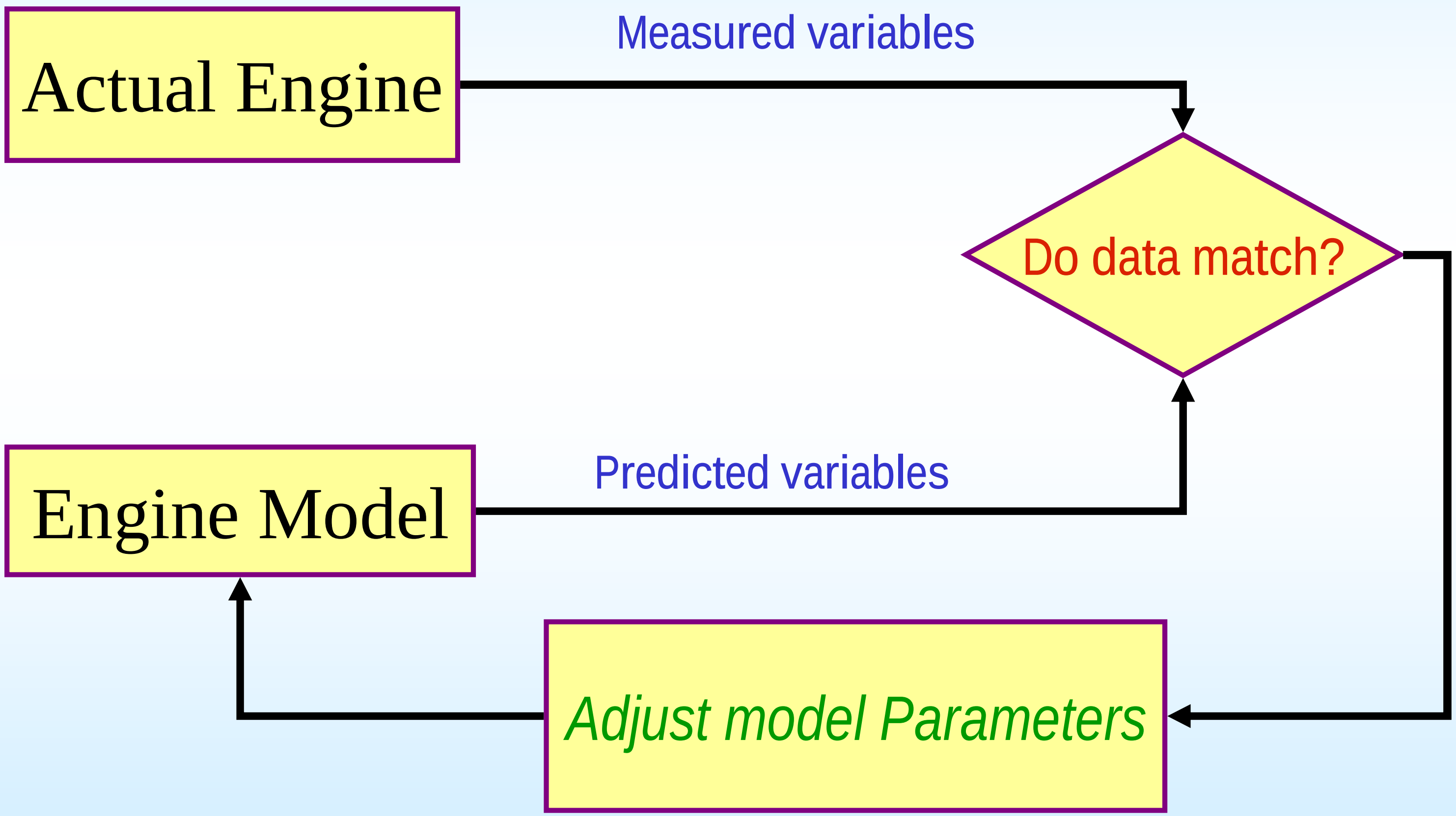
- **Structure of adaptive models**
- **Adaptive model of a partially mixed turbofan**
- **Implementation aspects**
- **Diagnostic effectiveness and timing investigations**
- **Discussion**
- **Conclusions**

Why Adaptive models?

- **Individual engines of a particular model *are not identical***
- **One particular engine alters with time *(aging, deterioration)***
- **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

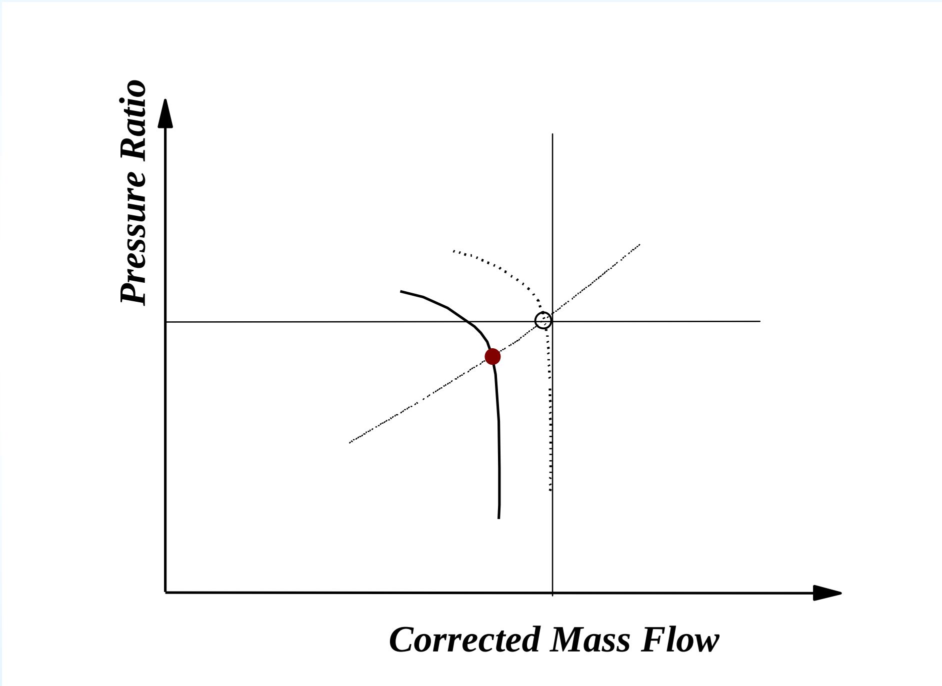
$x_{p,k}$: Actual value for parameter

$x_{p,ref,k}$: 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

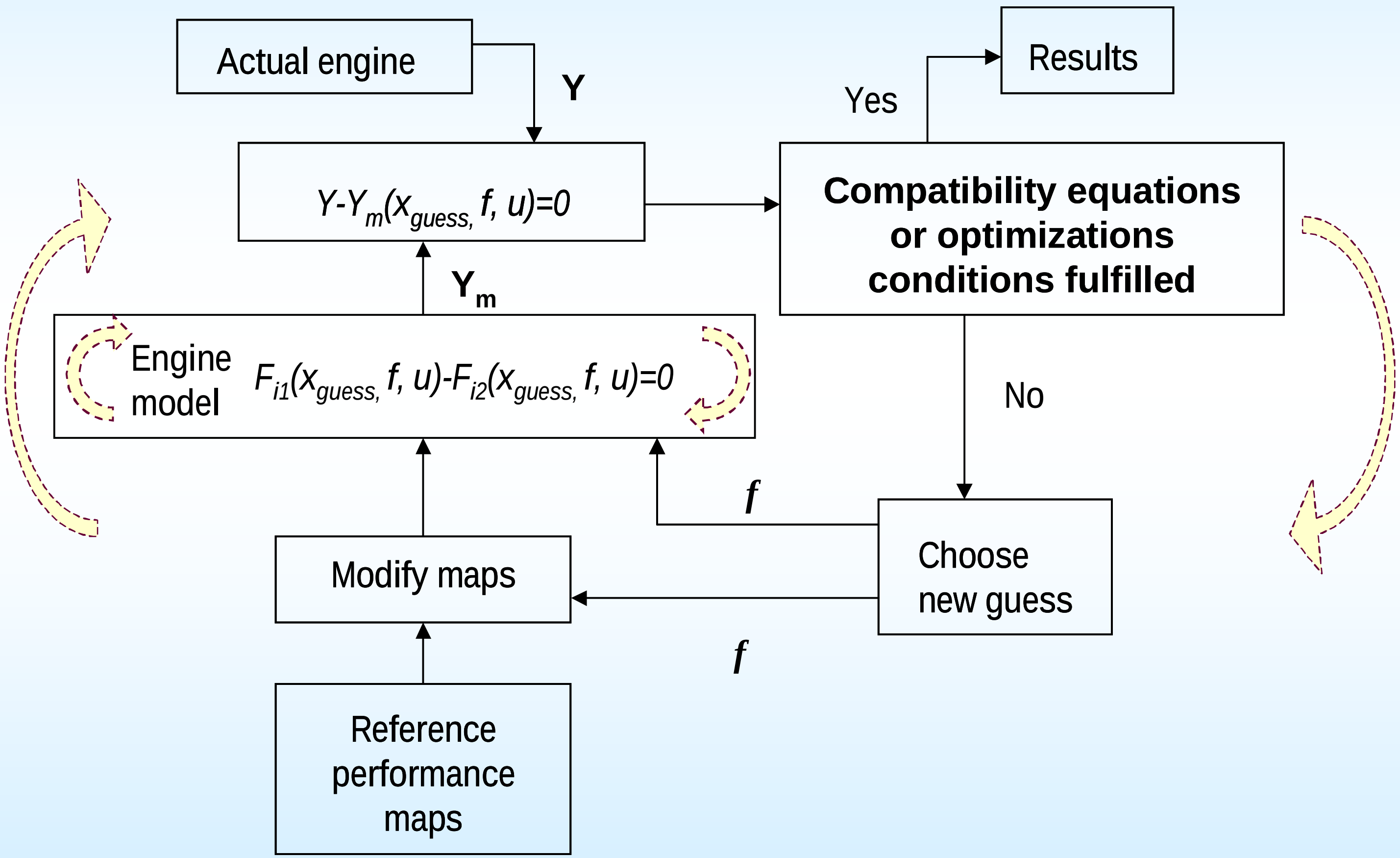
External

Separate solution for error and adaptation equations

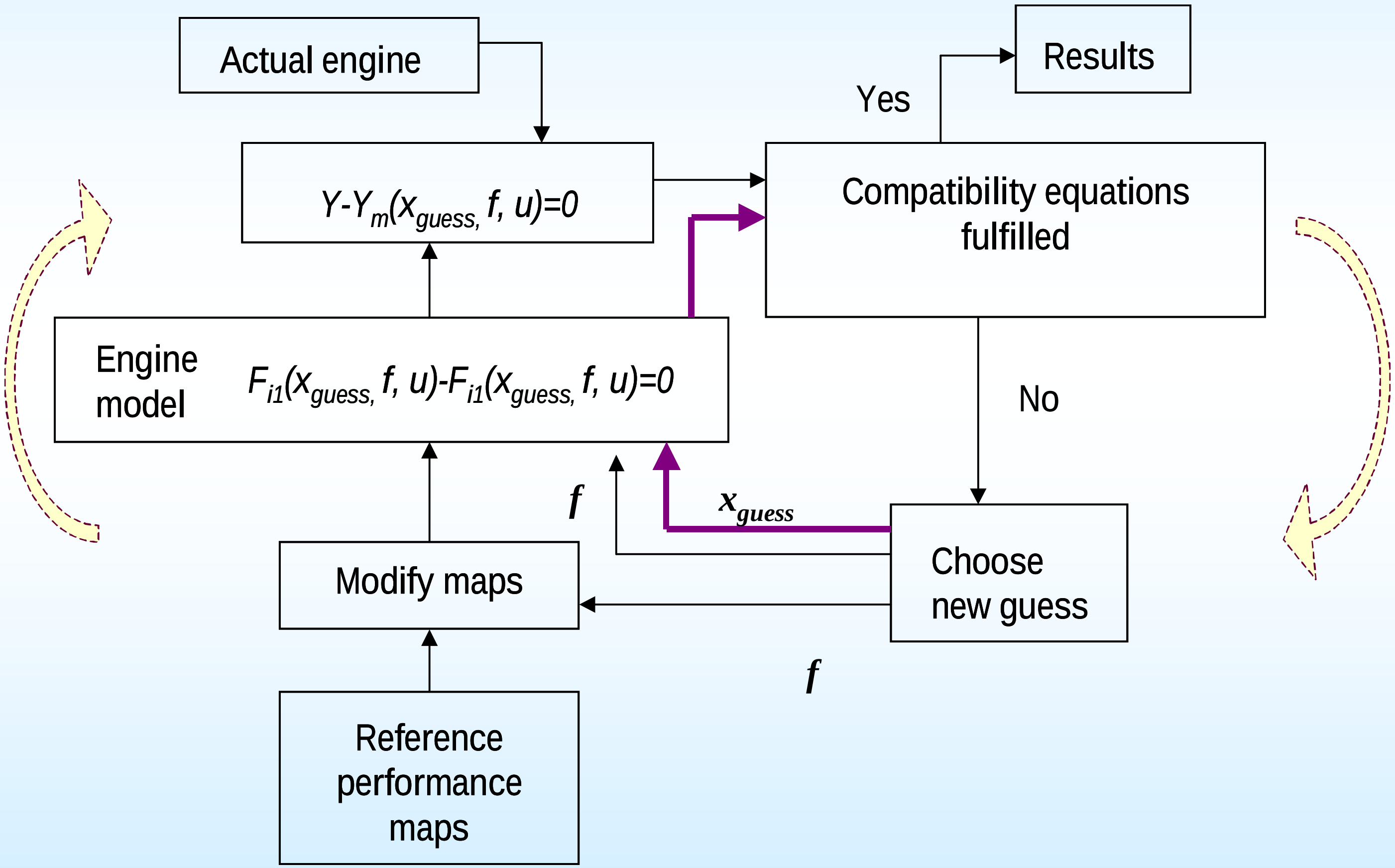
Internal

Concurrent solution of error equations $\boldsymbol{F}_i(\ )=\boldsymbol{0}$ and adaptation $\boldsymbol{Y}-\boldsymbol{Y}_m(\ )=\boldsymbol{0}$

External Adaptation



Internal Adaptation



Turbofan adaptive model presentation

Input parameters

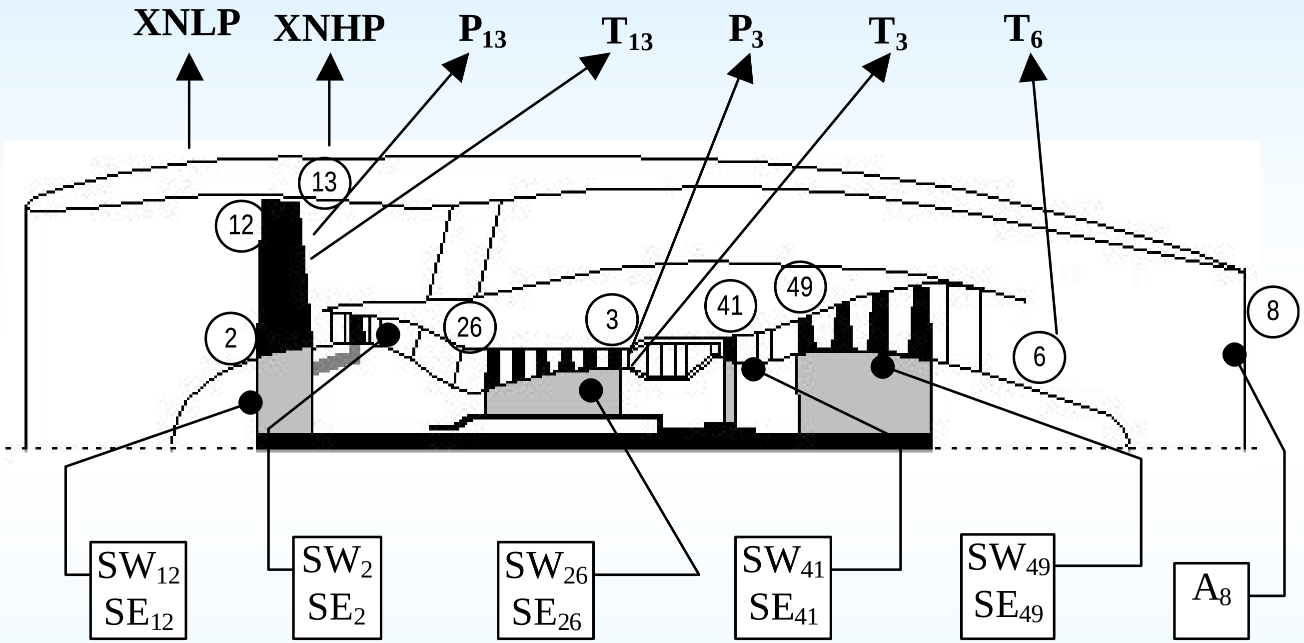
- **Quantities defining the operating condition (*u* vector)**

- **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



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

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

$$A8IMP = \frac{A8}{A8_{ref}}$$

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}
	Operation Point Definition	
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

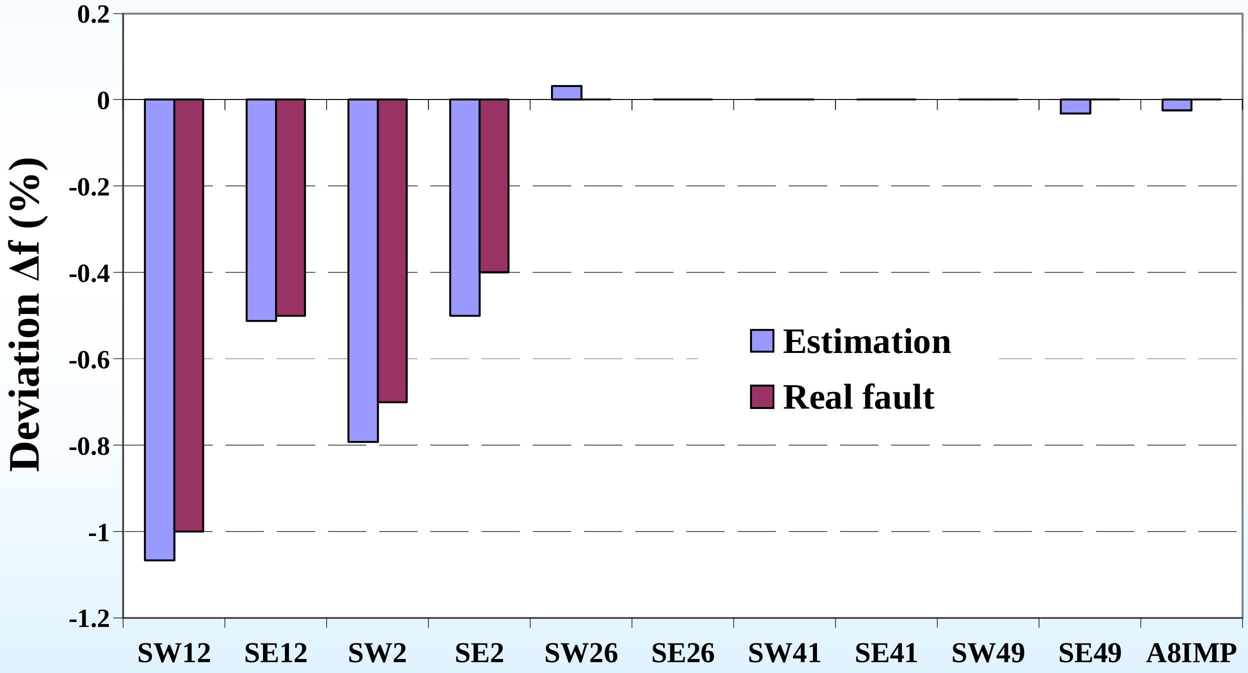
Sample Test Cases Examined

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

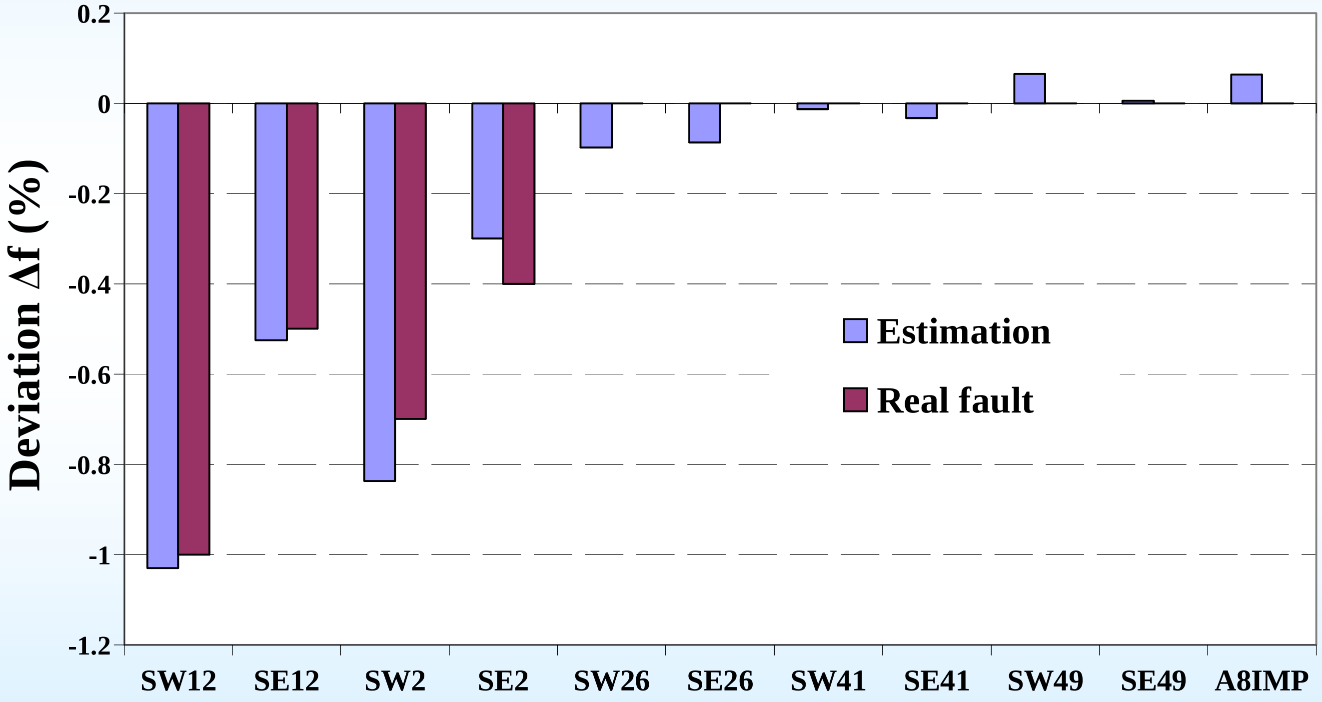


Adaptation time equal to 1x Simulation Time

Diagnostic effectiveness and timing investigations

Solver: Hill Climbing
Adaptation: External 7x11

Test Case 6



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

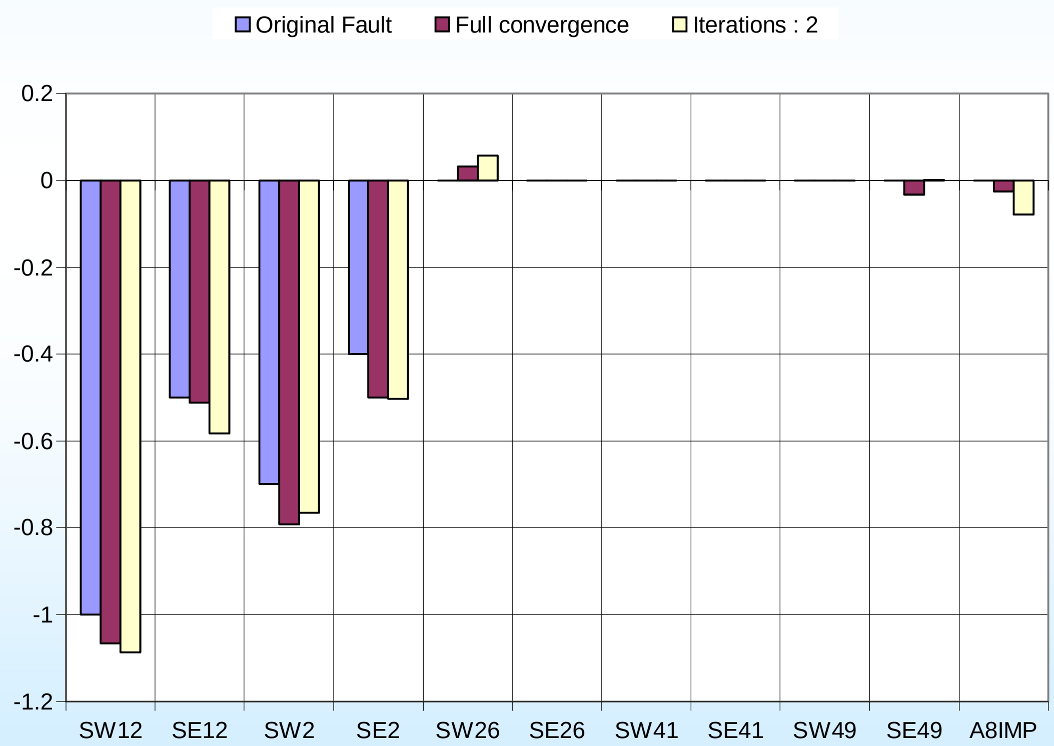
- Effect of fixed number for iterations
- Forms of tested objective functions
- Effectiveness of numerical methods
- Features of adaptive models
- Turbofan engine simulator software

Effect of fixed iterations

Solution algorithm: Newton type

Effect of fixed number of iterations to estimation

Internal adaptation, 7x7



Forms of tested objective functions

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

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

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

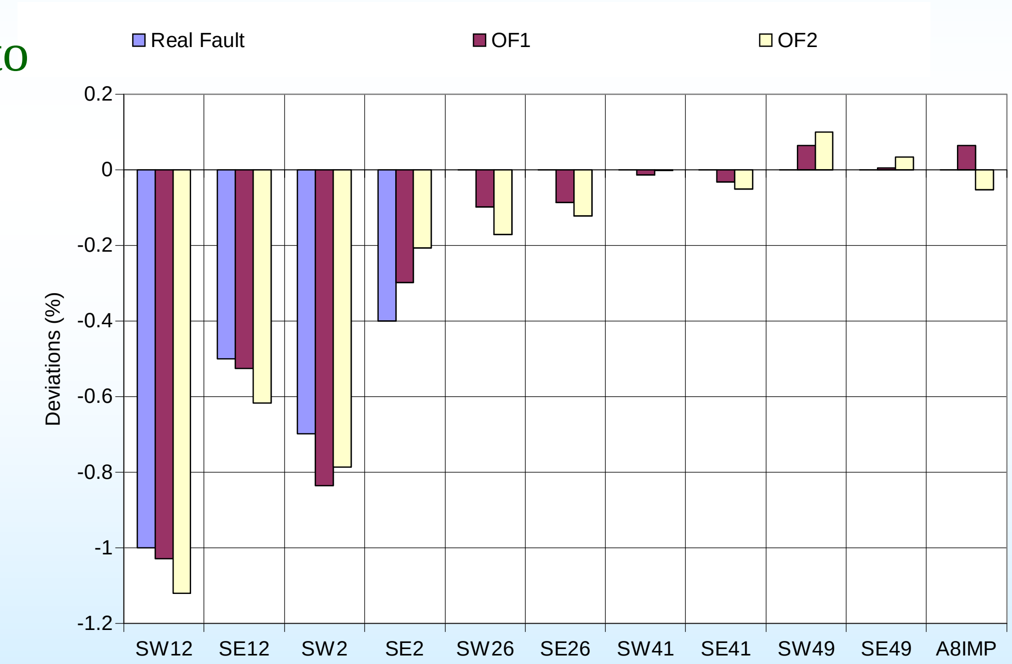
Test of several forms of objective functions

Test Case: Fault

Solution algorithm: Hill Climbing

Effect of objective function to estimation. Case: Fault

External adaptation, 7x11



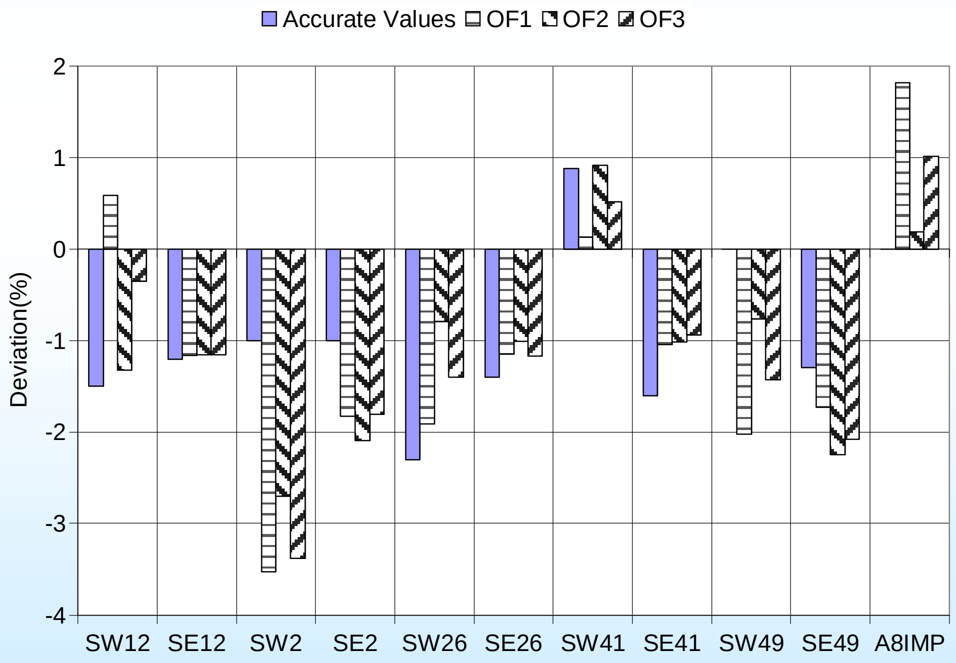
Test of several forms of objective functions

Test Case: Deterioration

Solution algorithm: Hill Climbing

Effect of objective function to estimation. Case: Deterioration

External adaptation, 7x11

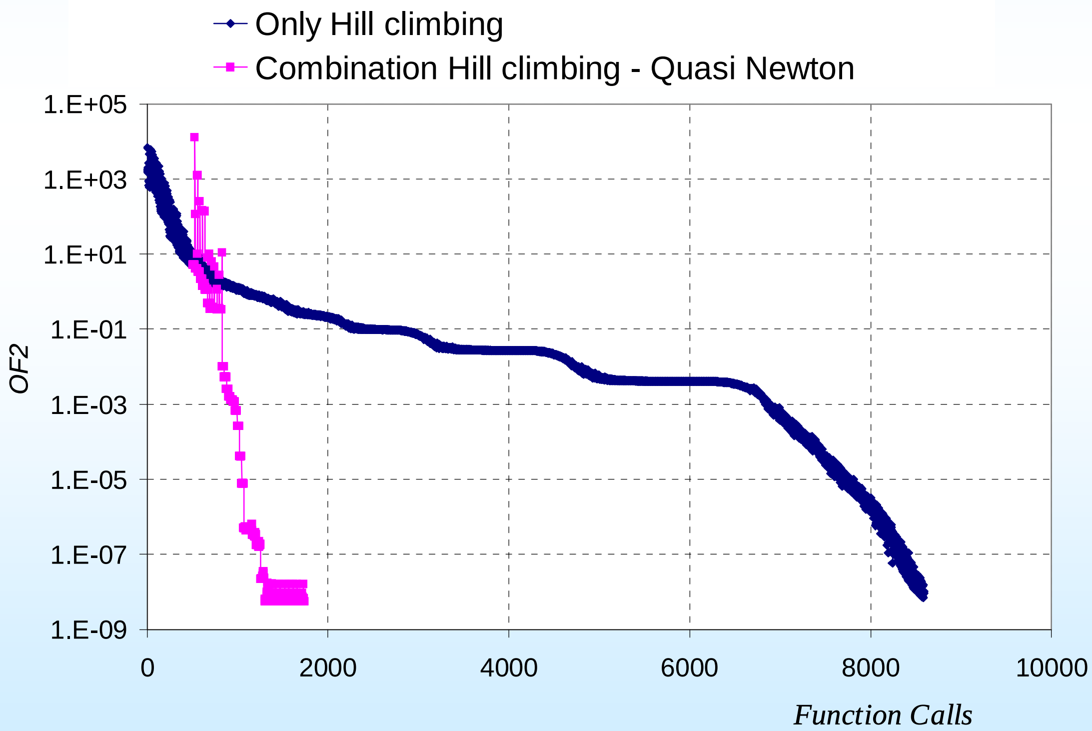


Effectiveness of numerical methods

Hill climbing versus Quasi-Newton

Case: Fault

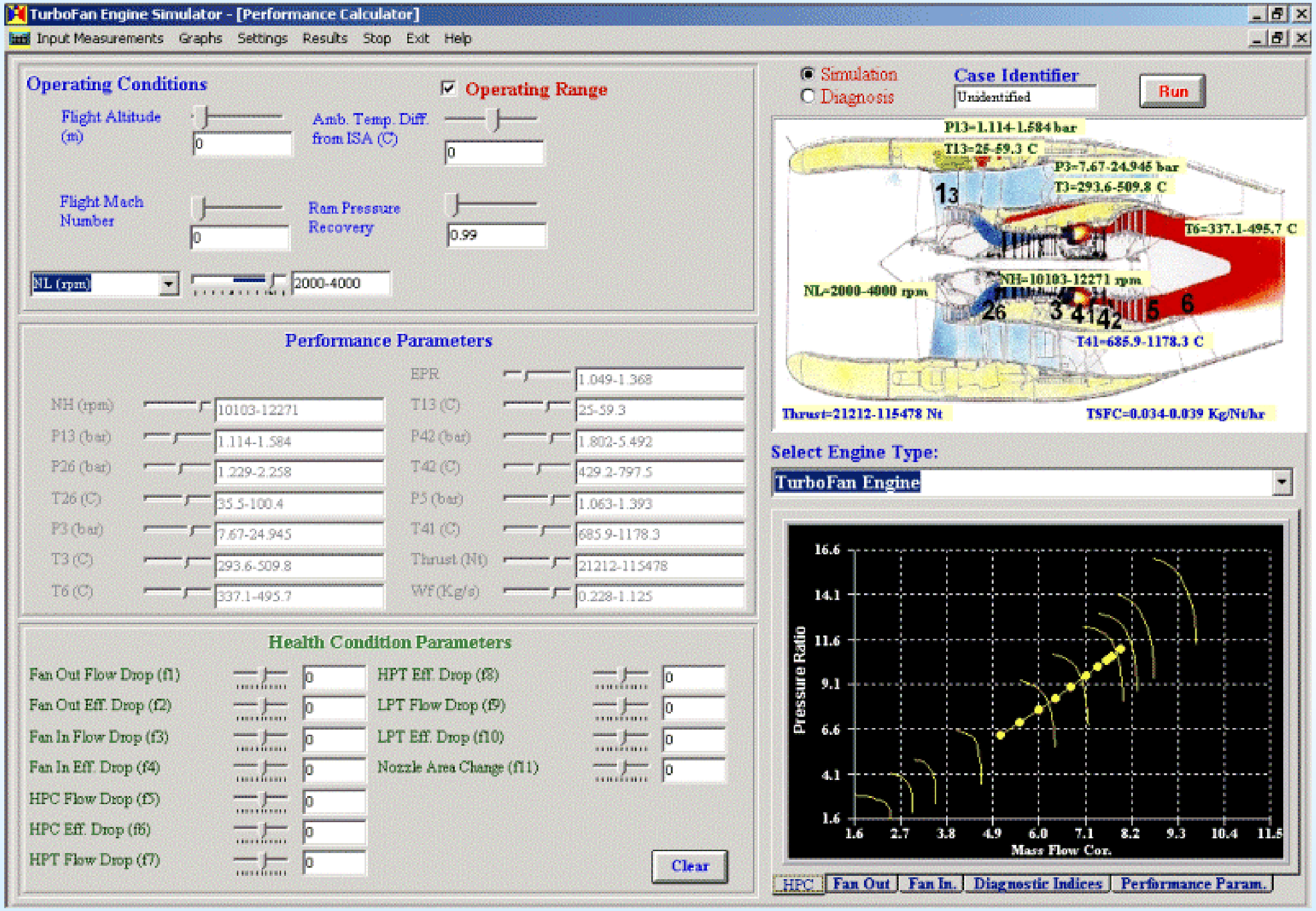
External adaptation, 7x11



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



Demo available at 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**