# Analisi dello stato di funzionamento di turbine a gas

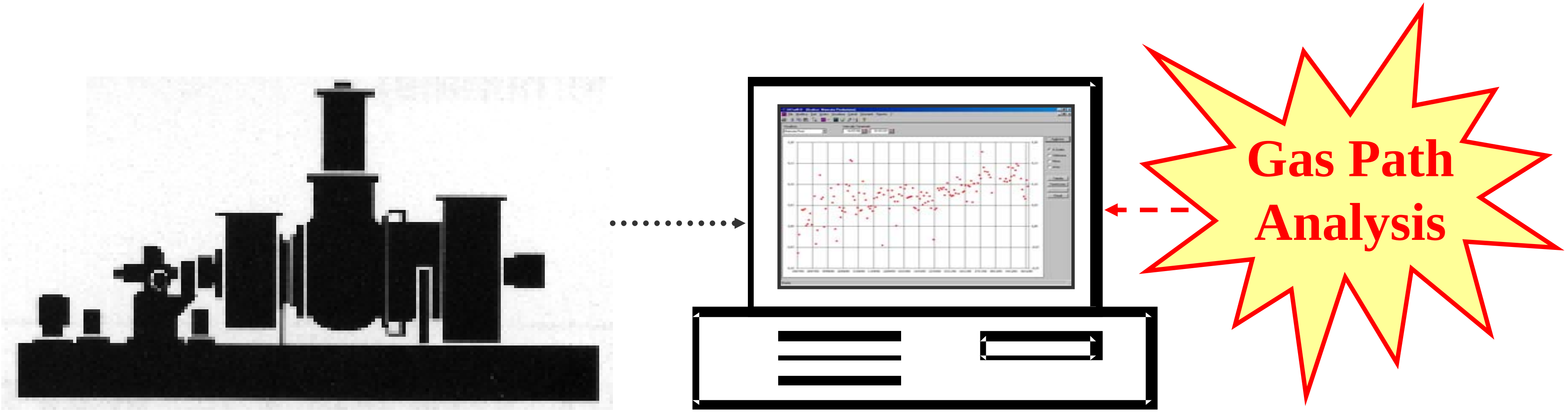


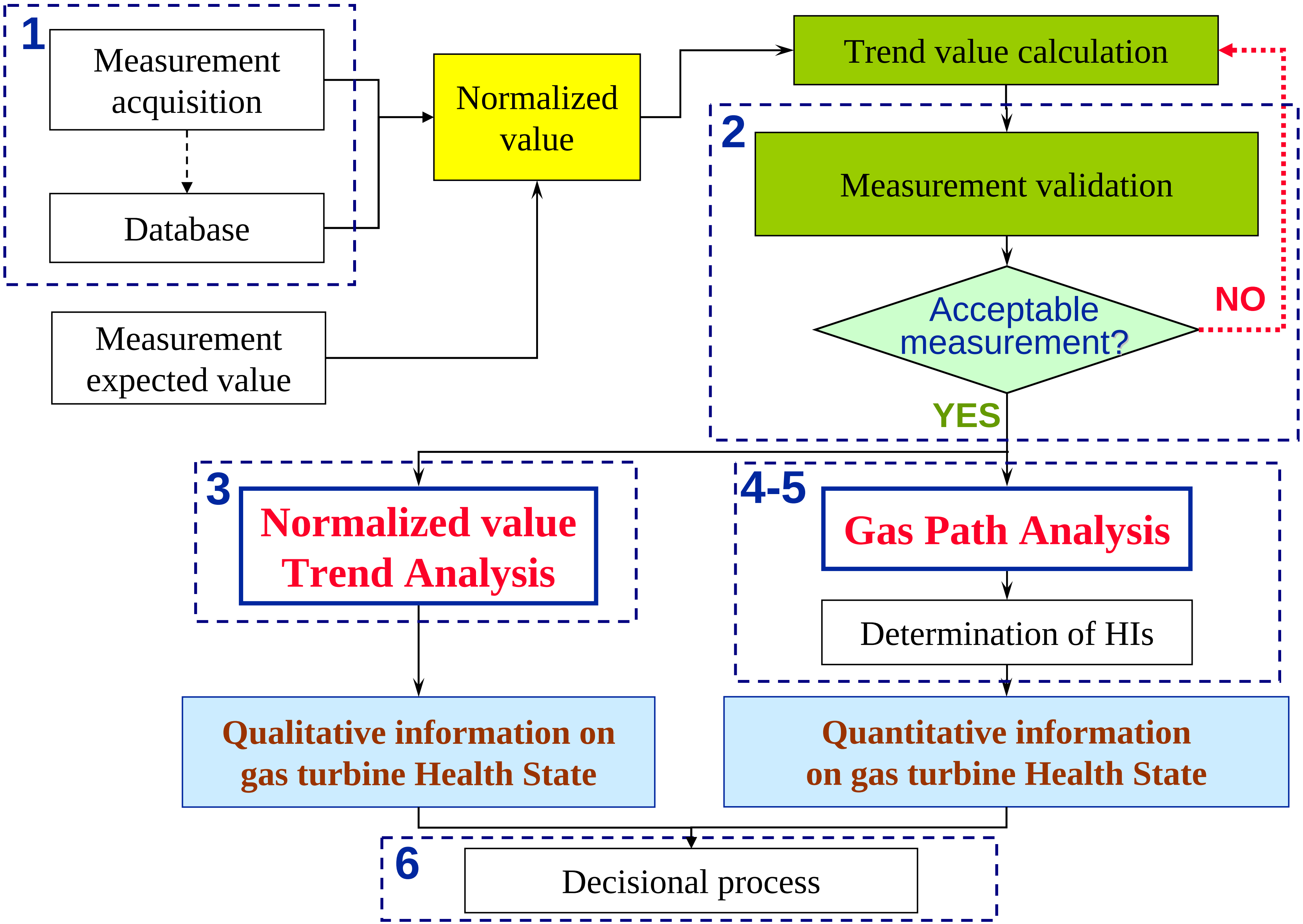
university of ferrara
600 YEARS OF LOOKING FORWARD.

# Gas turbine operation optimization

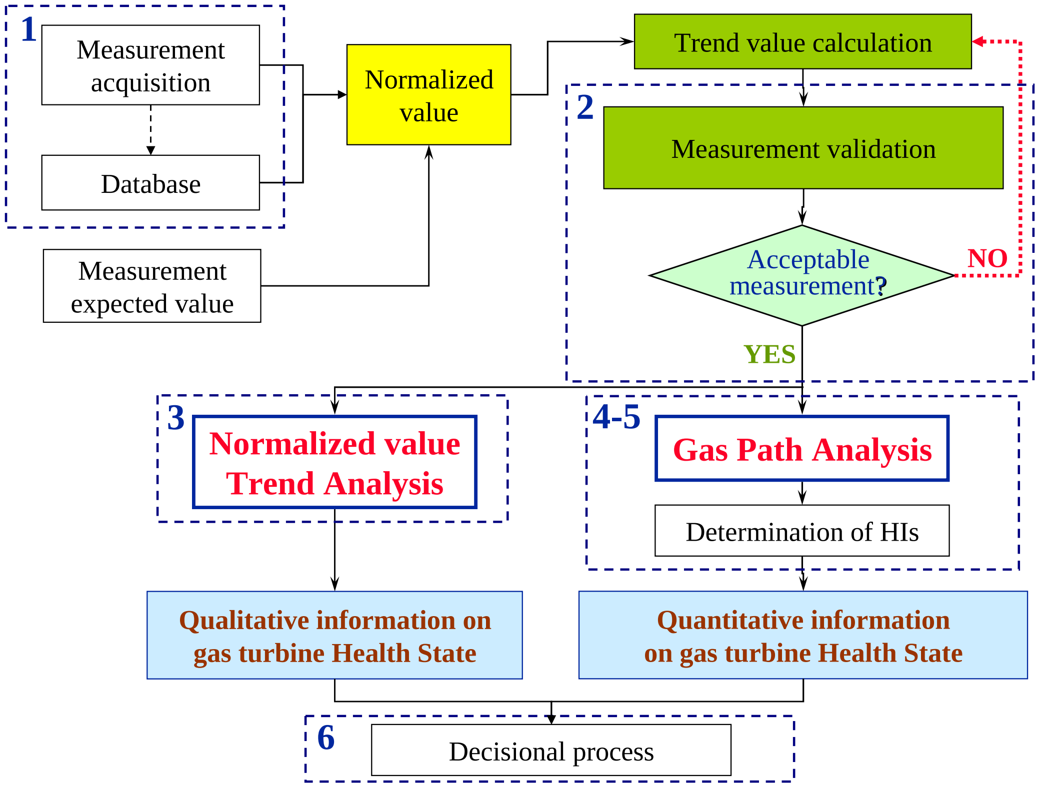
**GT *on-condition* maintenance**

- **Maintenance costs ↓**
- **Management costs ↓** (Non-scheduled stops ↓)
- **Process interruption ↓** (Availability ↑)



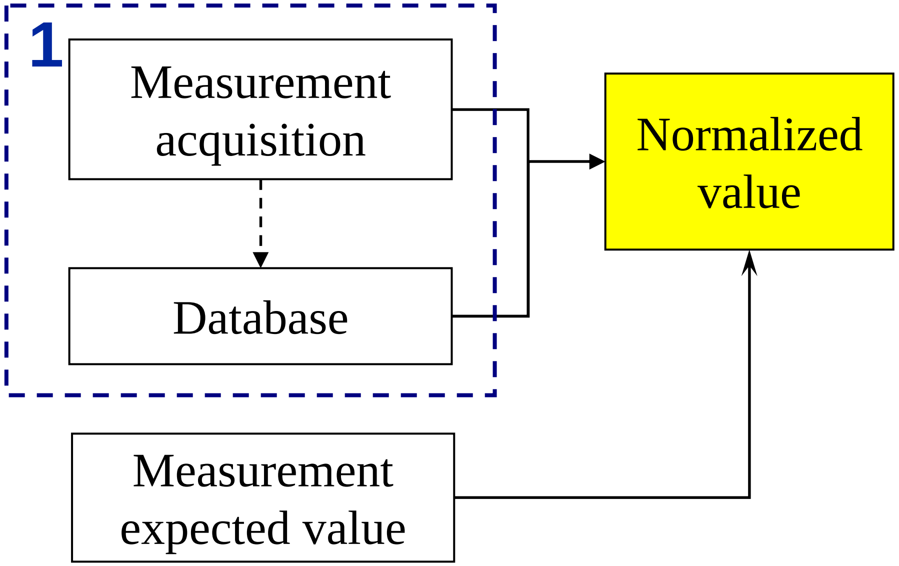

1
Measurement acquisition
Database
Normalized value
Measurement expected value
Trend value calculation
2
Measurement validation
Acceptable measurement?
NO
YES
3
Normalized value Trend Analysis
4-5
Gas Path Analysis
Determination of HIs
Qualitative information on gas turbine Health State
Quantitative information on gas turbine Health State
6
Decisional process

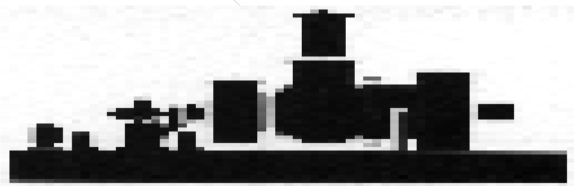
# The diagnostic process




| | |
|---|---|
| ✓ **Field measurements** | ✗ **Measurement accuracy** |
| ✓ **Thermodynamic Cycle Program** | ✗ **CP tuning** |
| ✓ **Health Indices** | ✗ **Measurement number** |

# The diagnostic process (1/4)



Field measurements $\mathbf{Q_m}$

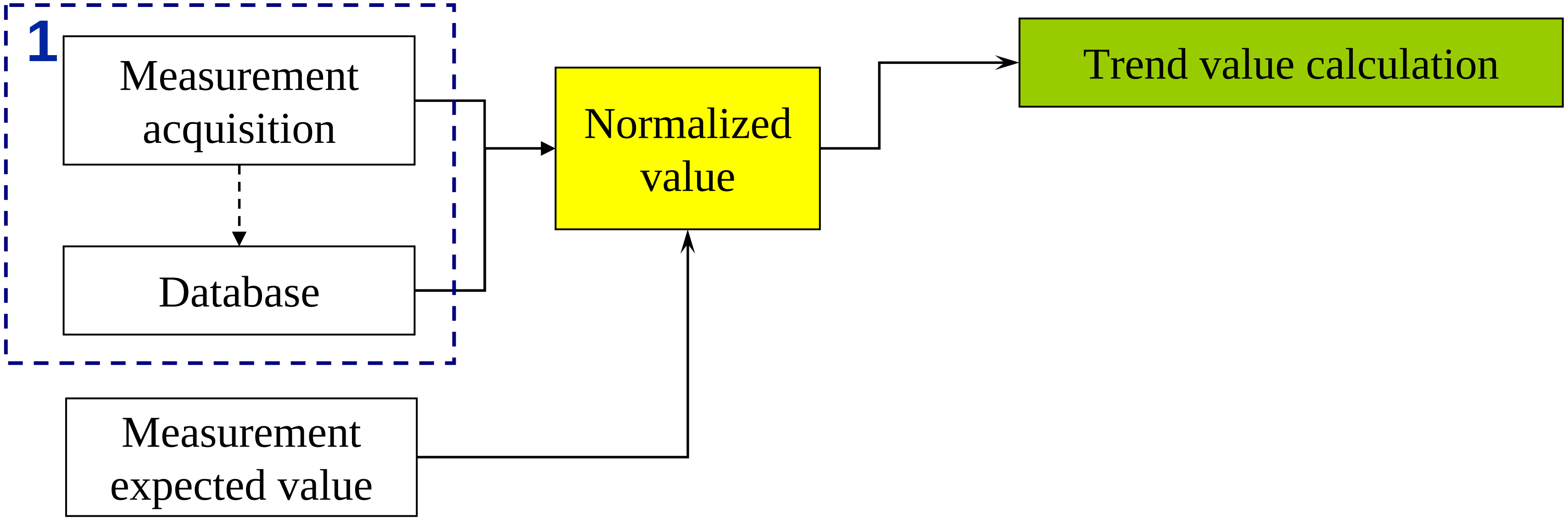
Cycle Program

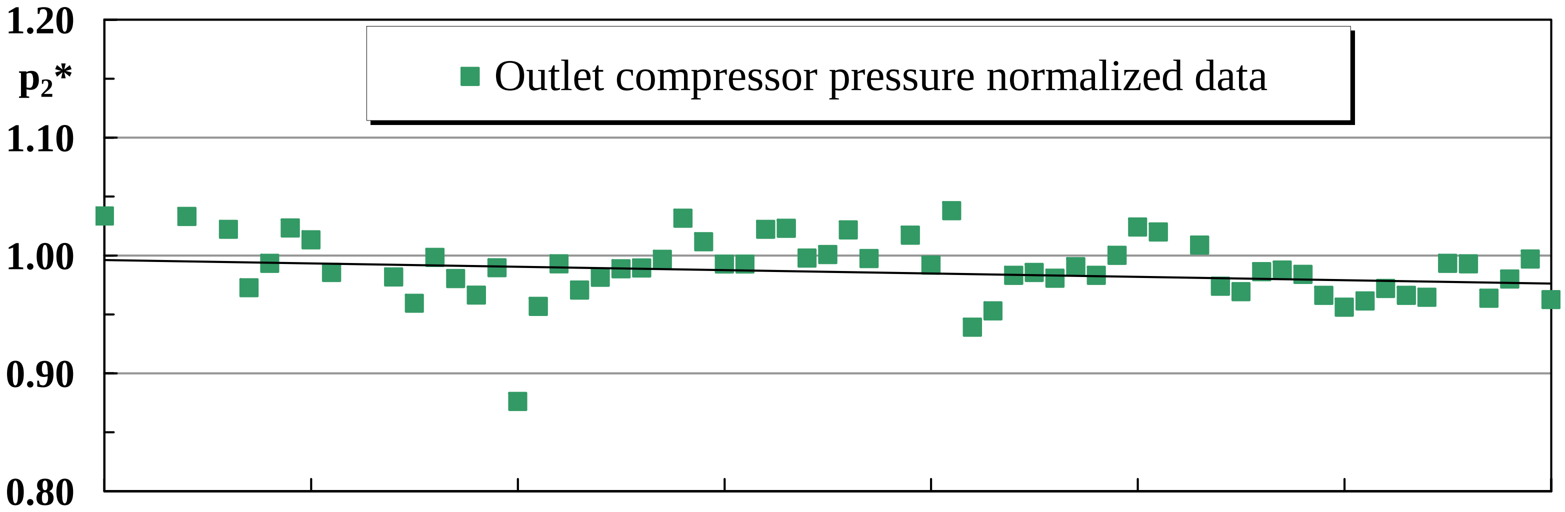
Expected values $\mathbf{Q_m}$’

**Normalized value**

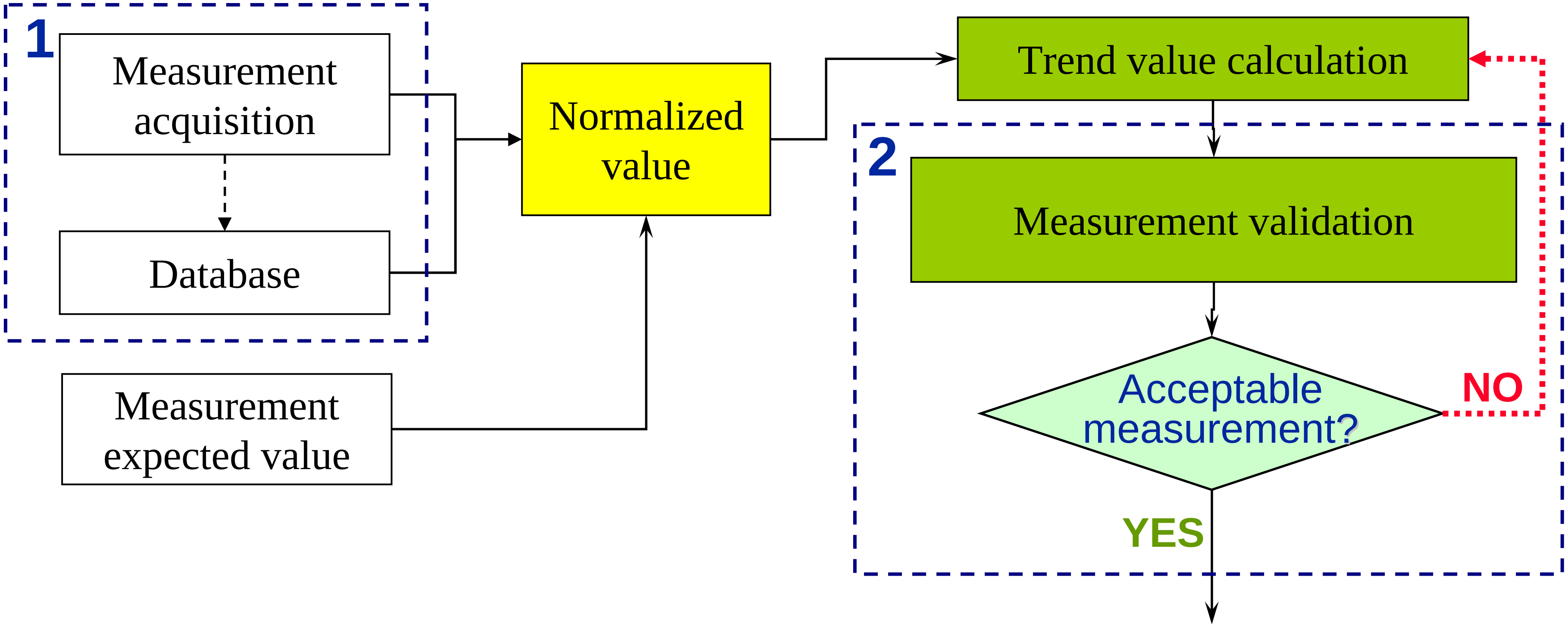
$$Q_m^* = \frac{Q_m}{Q_m^{'}}$$

# The diagnostic process (2/4)



# The diagnostic process (3/4)



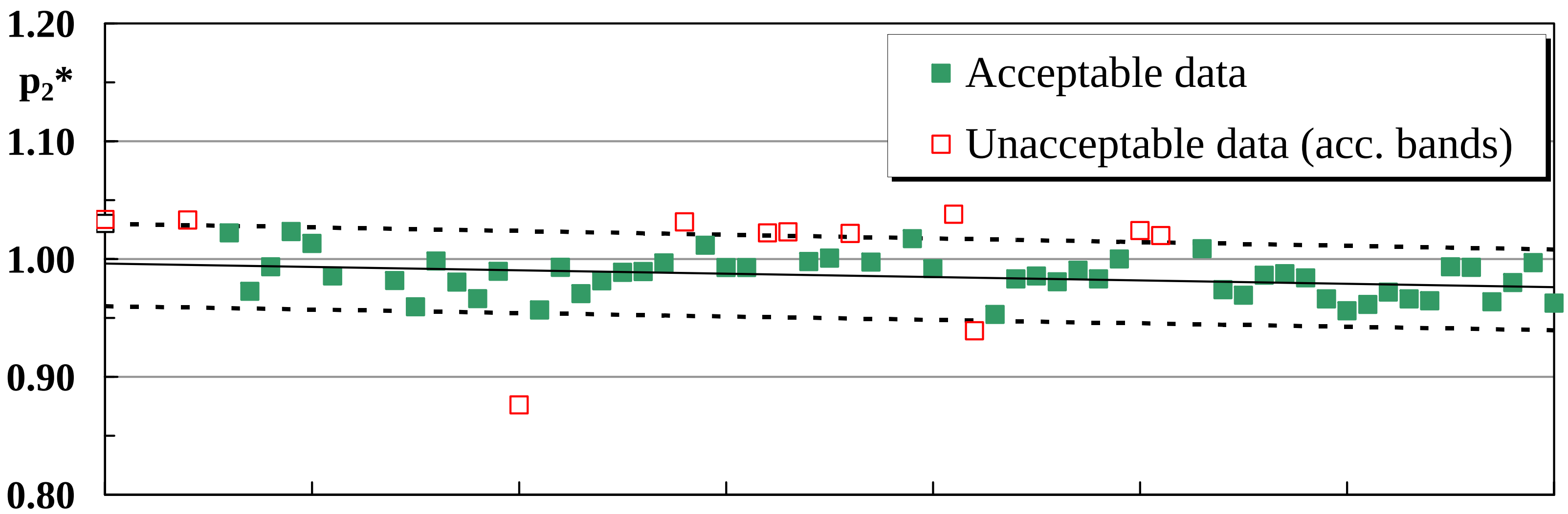

**Two techniques**
both applied to the normalized trend over time of each measurement

- ✓ **Measurement acceptability bands**, which consider (1) meas. accuracy + acquisition system noise, (2) engine faults and (3) CP tuning accuracy
- ✓ **Statistical technique for outlier detection** through a test criterion, i.e. analysis of the statistical distribution of the normalized measurement trend

# Measurement validation through acceptability bands

## Band amplitude: measurements accuracy and total band amplitude

| Measured Quantities | Measurements accuracy [% of reference value] | Confidence band [% of trend value] |
|---|---|---|
| $T_2$ | ±0.85 | [-1 ; + 5.5] |
| $p_2$ | ±1.00 | [-4; + 3] |
| $T_6$ | ±0.75 | [-1 ; + 5.5] |



# Measurement validation through statistical techniques

$$\frac{|x_i - x_\mathrm{m}|}{S} \geq k, \qquad i = 1,\ldots,N$$

- Practical and easy-to-use
- Robust

$x_\mathrm{m}$ = mean of the sample ($N$ = sample size)

$S$ = standard deviation

$k$ = threshold, which depends on sample size $N$ and on the level of significance $\alpha$

$\alpha$ = probability of rejecting a good point (usually < 5 %)

**If the inequality applies, $x_i$ is an outlier.**

- Available methods in literature: Thompson method, Grubbs method, Chauvenet criterion, …
- These methods proved only partially effective for GT data (in fact, trends are usually not constant over time)
- Thus, a new method was developed by the authors

# Statistical technique developed by the authors

$$\frac{|x_i - x_m|}{k_B S} \geq t_\alpha k_A, \qquad i = 1,\ldots,N$$

- The new coefficients account for the behavior-in-time of each quantity

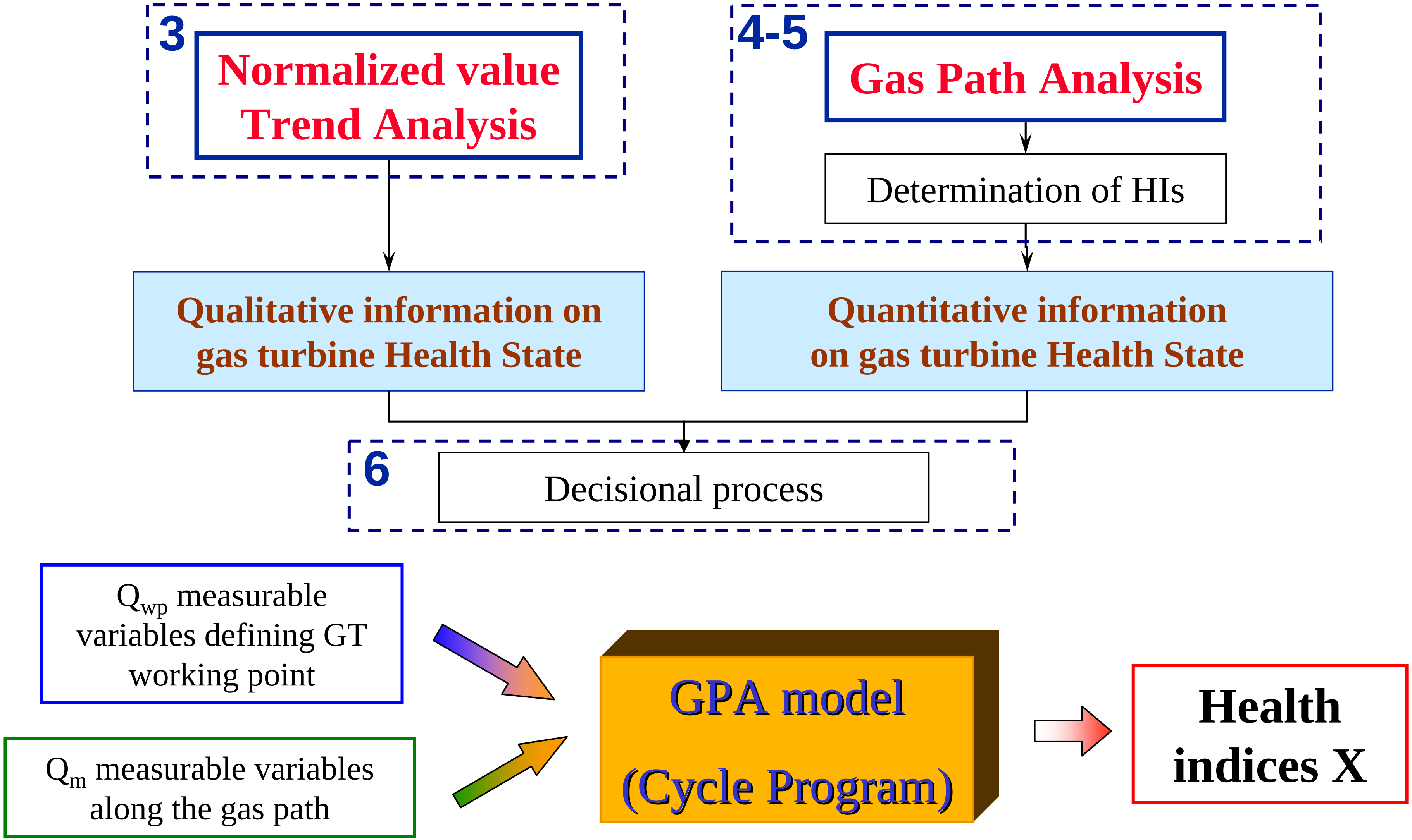
$$k_A = 1 + \frac{\lim_{N\to\infty} t_\alpha^2 + 1}{4N}$$

- $k_A$ tends to one when $N$ tends to infinity
- $t_\alpha$ represents the value of the quantile corresponding to a certain level of significance

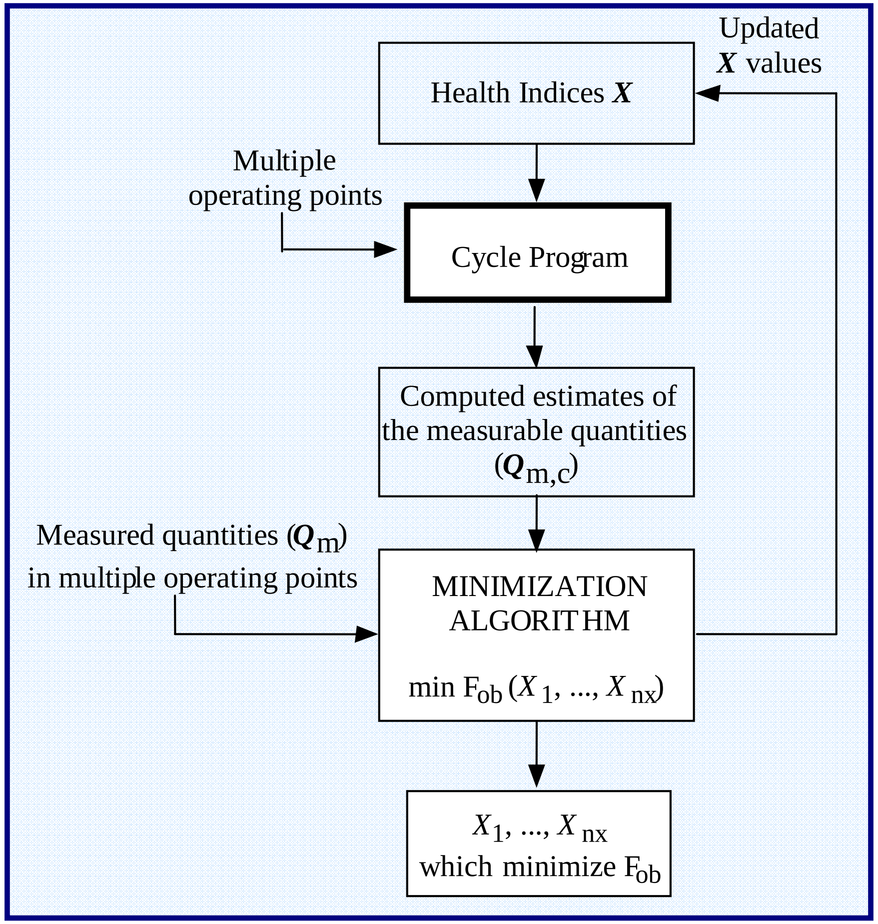
$$k_B = (1+N)^{\frac{1}{N}} \left(1 + |S_{ov} - S_i|\right)$$

- $k_B$ accounts for the scatter of the considered sample
- The left-hand side term of test criterion is updated at each step (off-line data processing!)

# The diagnostic process (4/4)



# Determination of GT Health Indices




GT Characteristic Parameters determination can be performed by **minimizing** $F_{ob}$

(sum of the square differences between measured and computed values of the measurable variables, performed on one or multiple operating points)

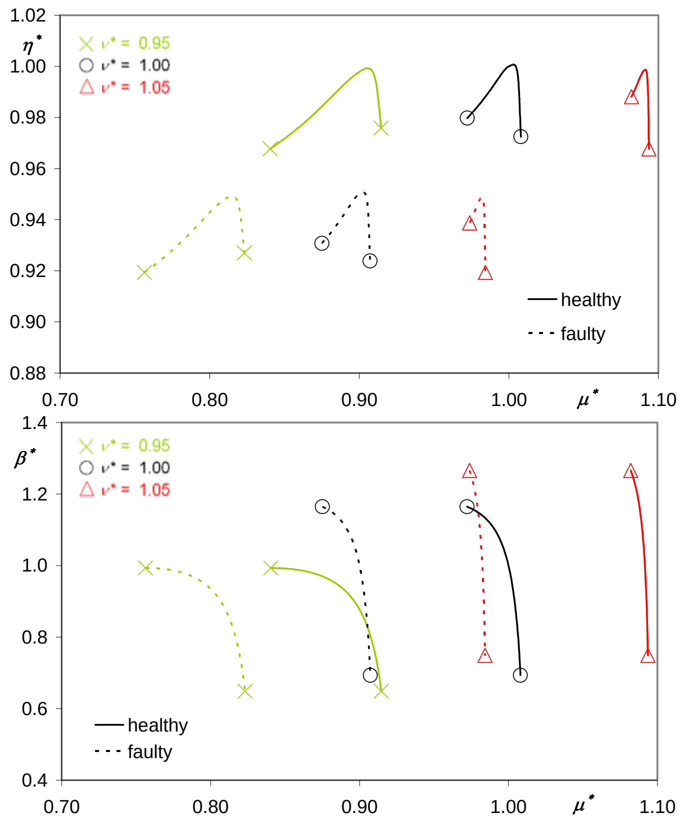
$$F_{ob}(X_1,\ldots,X_{N_x}) = \frac{1}{N_{op}} \sum_{j=1}^{N_{op}} \left[ \sum_{i=1}^{N_m} w_i \left( \frac{Q_{m,c} - Q_m}{Q_m} \right)_i^2 \right]_j$$

**Parameters variations with respect to their expected values in "new and clean condition" (all parameters =1) determines GT Health State**

# Fault simulation

Gas turbine operating state determination consists of the assessment of the modification, due to deterioration and fault, of performance and geometric data characterizing machine components.

Effects are usually simulated by multiplying **point by point** the performance maps in new and clean condition by **scaling factors**.



# Remarks on multi-point analysis

- When poor instrumentation is available, only few parameters can be determined and with a not-very-high accuracy

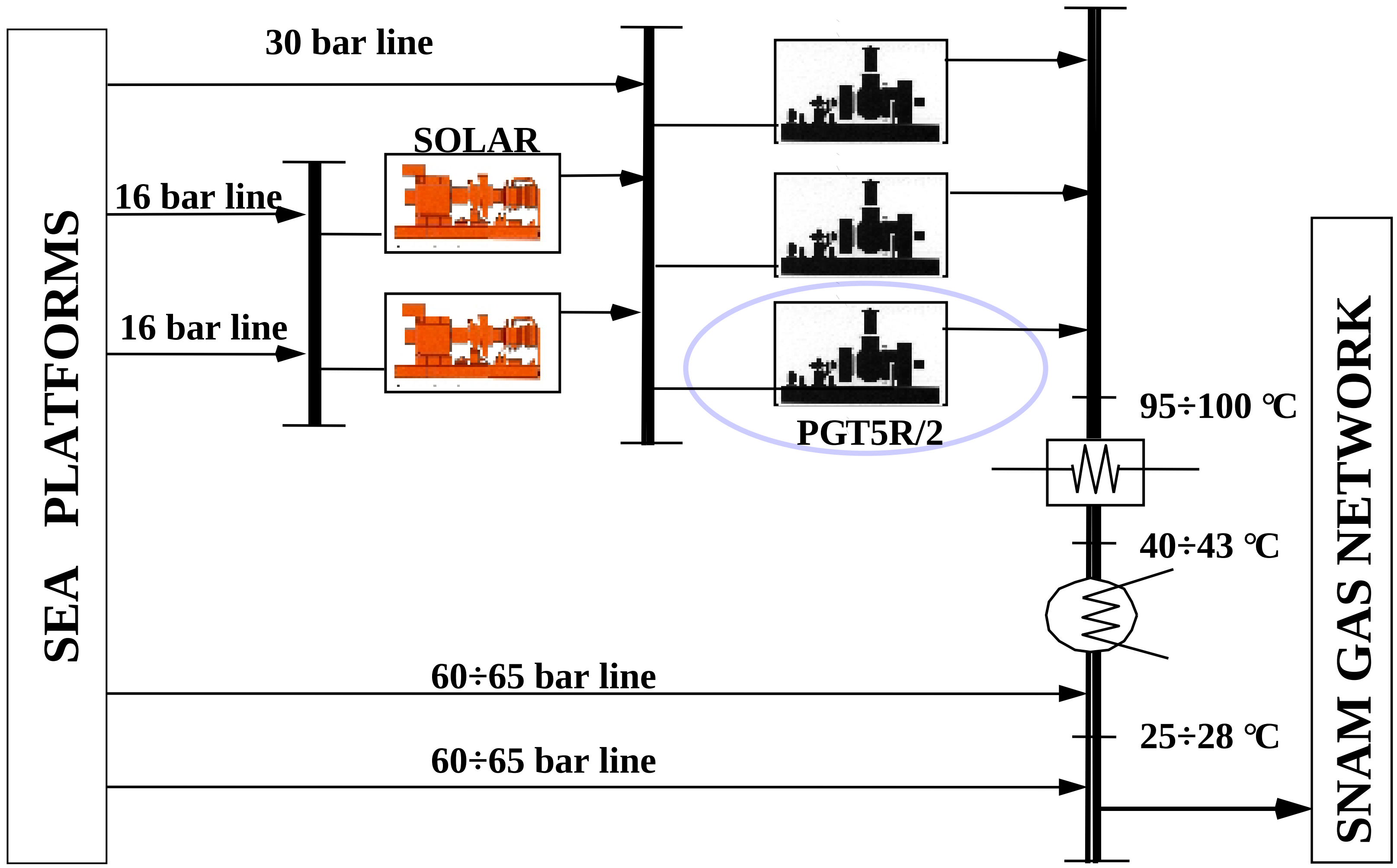
- To overcome these problems, Multiple Operating Point Analysis can be used.

  - The method determines GT Health Indices by processing measurement sets taken in different working conditions
  - The method compensates for the lack of measured quantities with the measurements taken at different operating points

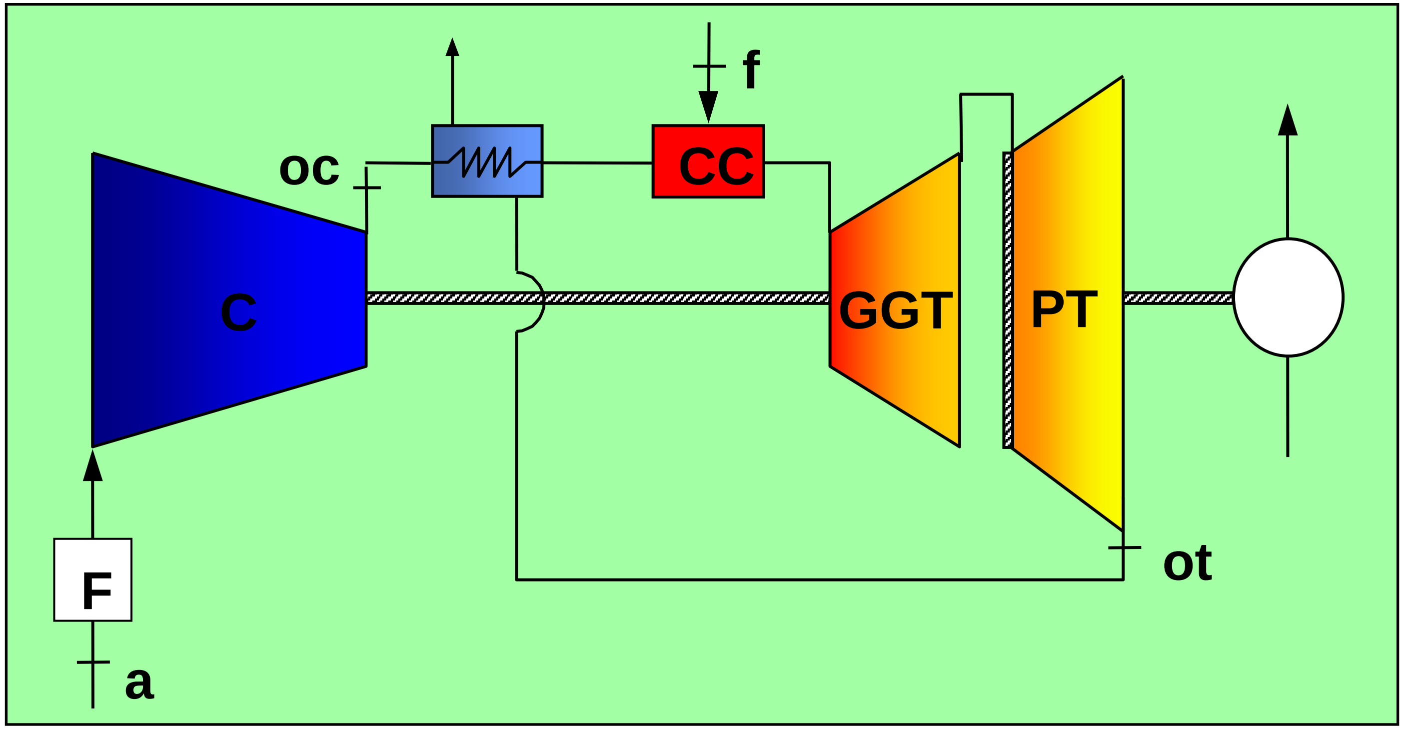
- By means of this method it is possible to:
  - calculate a number of $\mathbf{X}_{\mathbf{v}}$ > number of $\mathbf{Q}_{\mathbf{m}}$
  - improve accuracy

- In the following, the Multiple Operating Point Analysis will be applied **before** and **after** a **maintenance stop**

# Application to a natural gas compression plant



# Lay out of the 5.2 MW PGT5R/2 gas turbine




**Six** $Q_{wp}$ meas. to define the working point: $N_{GGT}$, $N_{PT}$, $P_{PT}$, $p_a$, $T_a$, $RH_a$

**Three** $Q_m$ meas. are available: $p_{oc}$, $T_{oc}$, $T_{ot}$

**Three** Health Indices can be determined: $\eta_C$, $\mu_C$, $\eta_{GGT}$

# Lack of measurement

- Lack of fuel mass flow rate measurement (**$M_f$**).

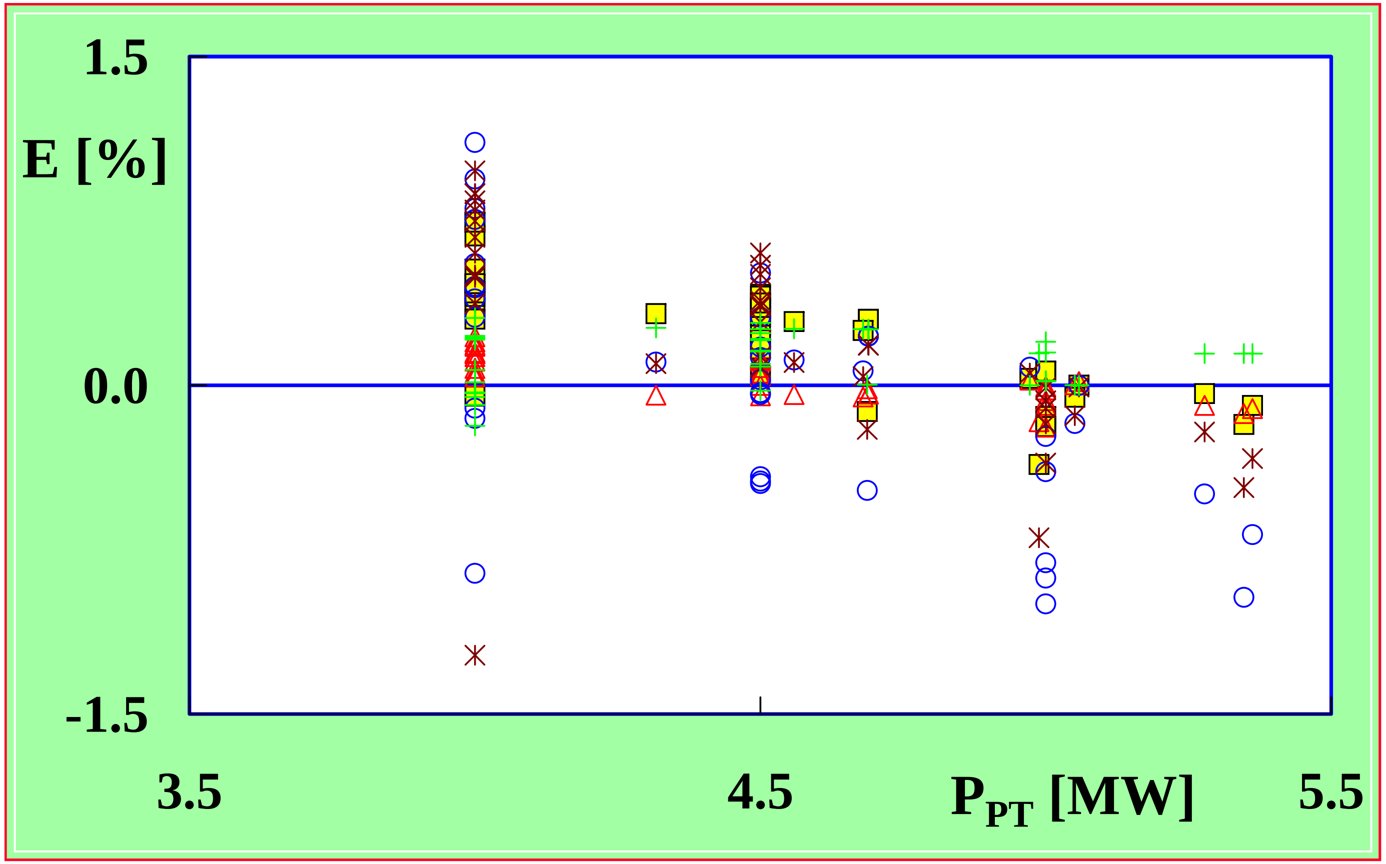
  Only the total fuel mass flow feeding the three PGT5R/2 GTs is available

- Other measurements not available:
  - pressure and temperature between the gas generator and the power turbine (**$p_{GGT}$, $T_{GGT}$**)
  - gas side and air side pressure drops of the recuperator (**$\Delta p_{air}$, $\Delta p_{gas}$**)
  - air inlet mass flow rate (**$M_a$**)

• The methodology was applied to a poorly instrumented plant, since it represents a selective test for the proposed diagnostic system

• Moreover, poor instrumented plants are highly widespread and, thus, the application to such cases seems particularly interesting

# Cycle Program calibration

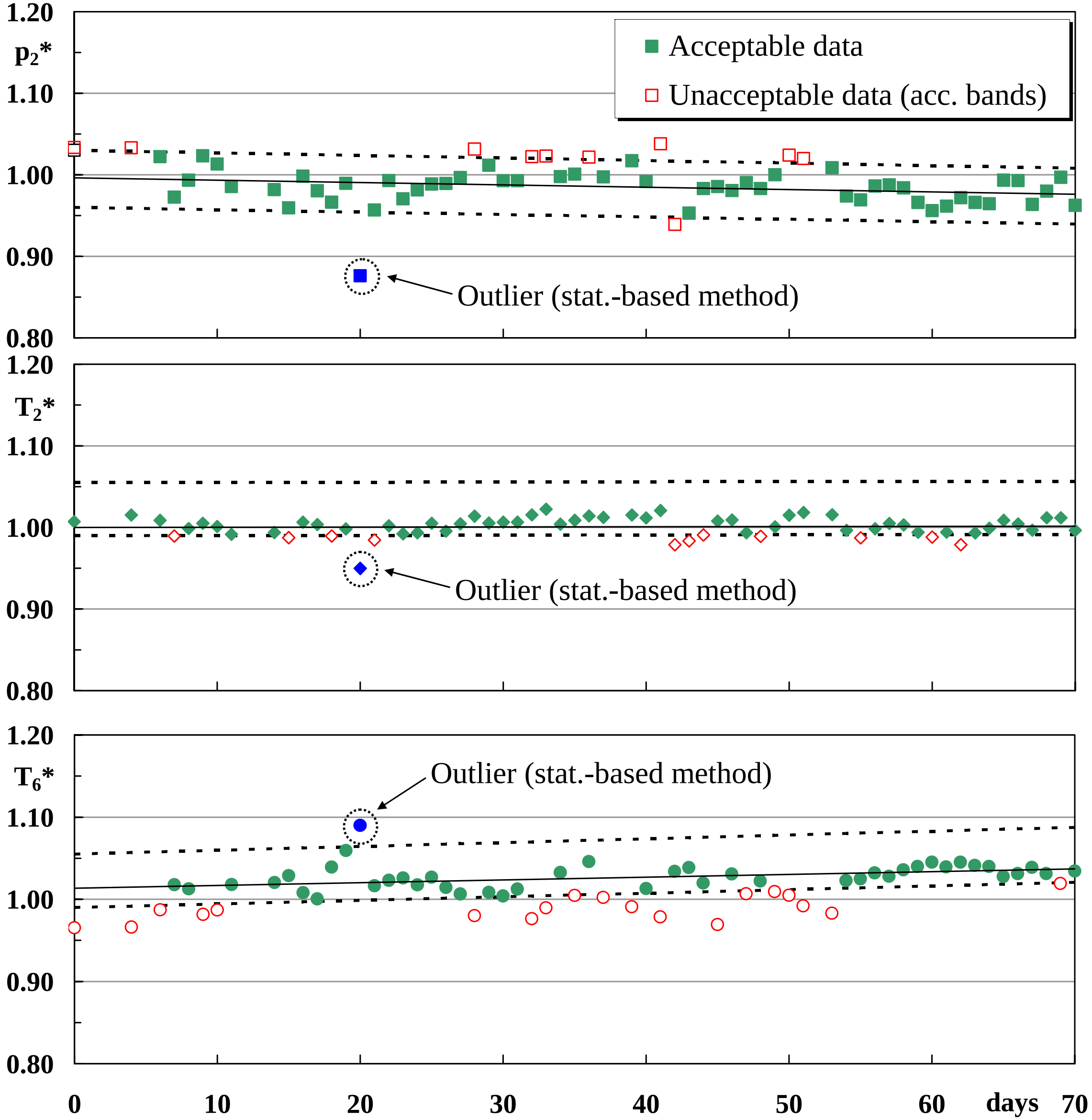



Errors between measured and computed value for

$M_{fuel}$ - $T_{ot}$ - $M_{air}$ - $T_{oc}$ - $p_{oc}$

**Six operating points (3.4 – 5.0 MW)**

# Normalized measurement trend analysis (Trend Analysis)



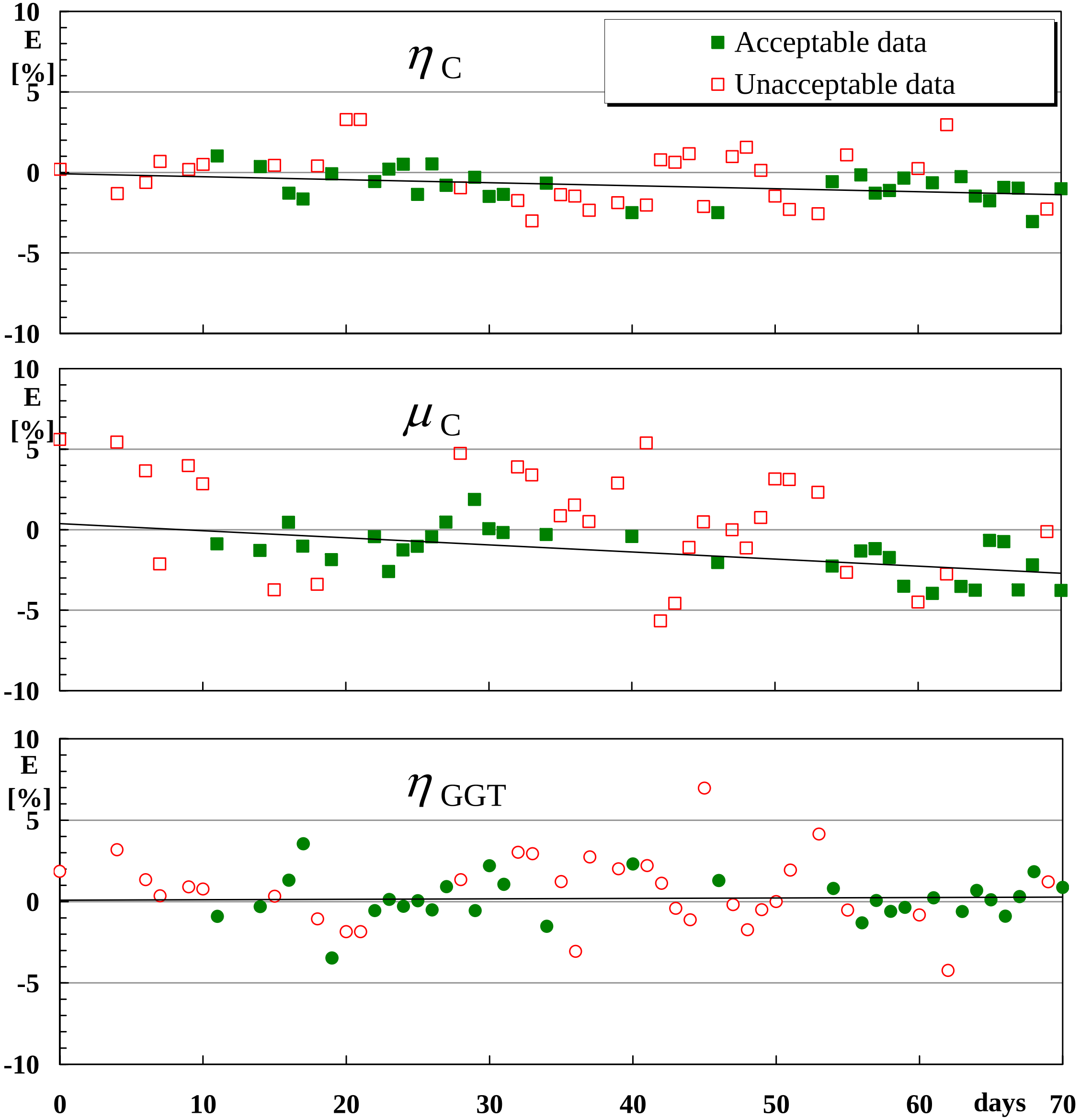

- Meas. scattering due to the uncertainties in field measurement readings

- The stat.-based method reveals that only one measurement set (day #20) is unacceptable. Thus, the stat.-based method is **less** restrictive than acceptability bands

- $p_{oc}$ ↓ (2 % in 70 days ) and $T_{oc}$ ≅ ⇒ comp. fouling

- $T_{ot}$ slightly ↑

# Health Indices estimation (single-point analysis)




- Remarkable reduction of the scattering of HI trends, by using acceptable measurement sets only

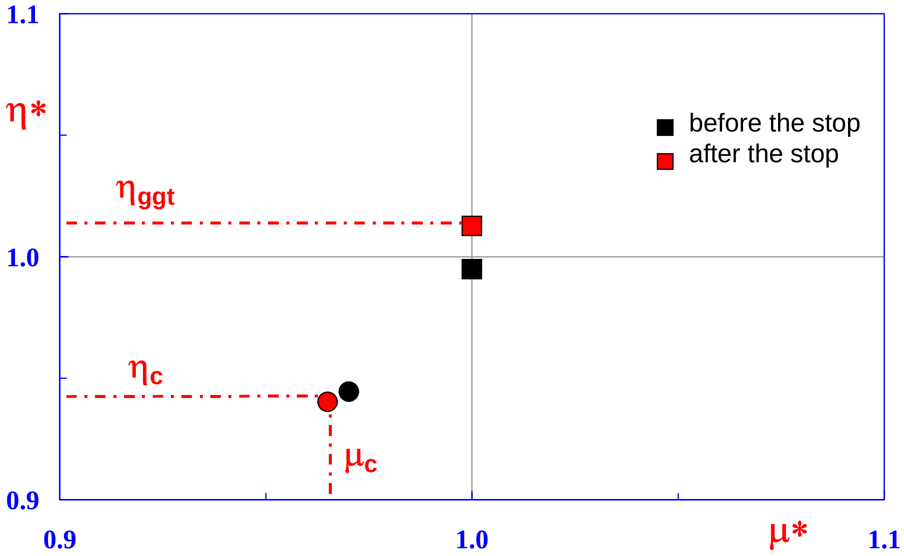
- Over a period of 2 months, $\eta_C \downarrow$ (1.0 %) and $\mu_C \downarrow$ (2.5 %) $\Rightarrow$ comp. fouling

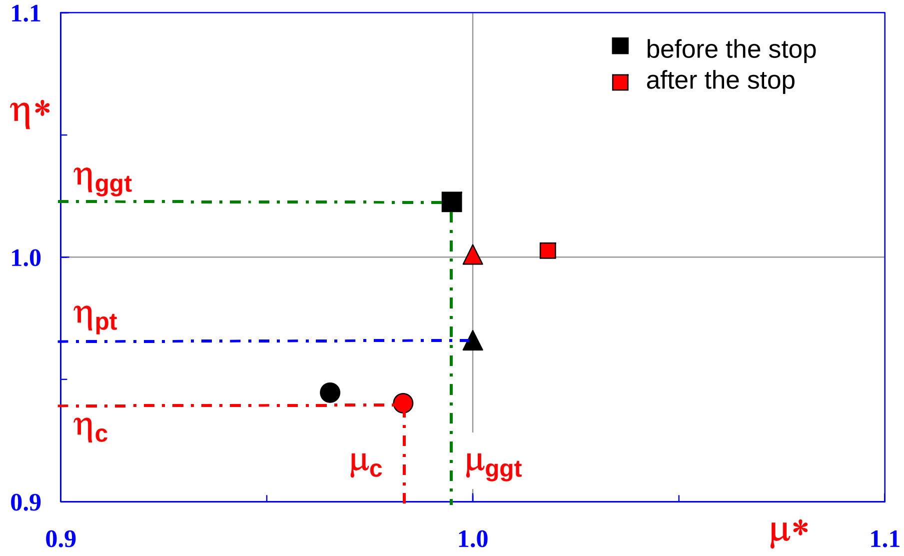
- $\eta_{GGT}$ almost constant $\Rightarrow$ no significant health state change

# Health Indices estimation (multi-point analysis)

**Three parameters** as problem variables $\eta_c$, $\mu_c$, $\eta_{ggt}$

**Five parameters** as problem variables $\eta_c$, $\mu_c$, $\eta_{ggt}$ $\mu_{ggt}$, $\eta_{pt}$



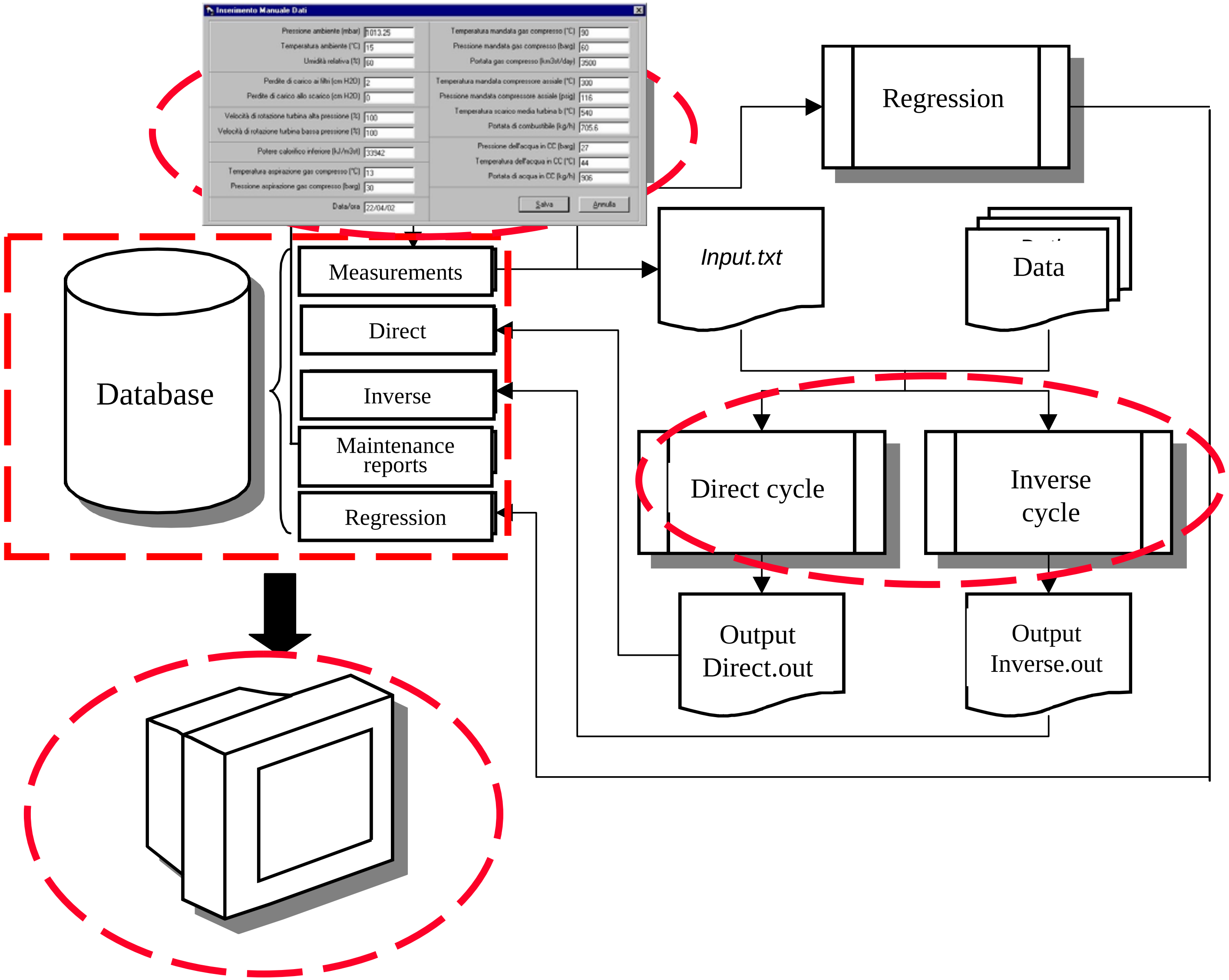




<u>More convincing results by using five HIs</u> as problem variables:

- 3-His ⇒ no improvement due to maintenance

- 5-His ⇒ increase in the corrected mass flows (both C and GGT)

# Health Monitoring System for the Compression Plant

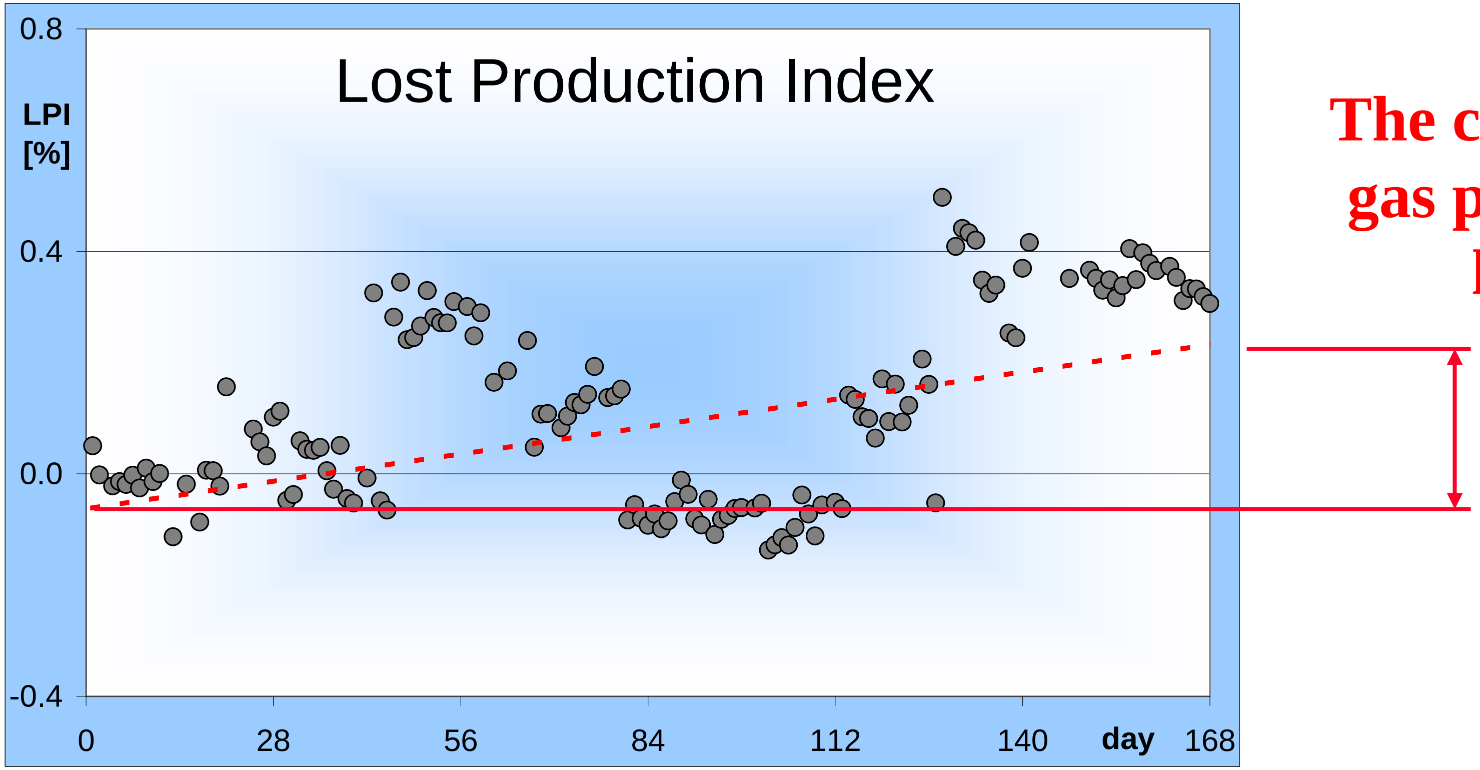


# Lost production index

$$LPI = \frac{Q_{gasC} - Q_{gasM}}{Q_{gasC}}$$

C = clean condition - M = measured

- LPI increase = decrease of actual production
- LPI quantifies (also economically) gas turbine loss of performance




**The compressed gas production loss is**

**+ 13 %**

# Conclusions

**The methodology proved effective in supporting plant operation and maintenance management:**

- Identification of unreliable measurements sets and remarkable reduction of the scattering of the measurement trends
- Gas turbine health state determination over a 2-month period: compressor fouling, while gas generator turbine was not suffering from significant changes in health state
- The multi-point analysis (applied before and after a maintenance stop) allowed a more detailed analysis
- Software to automate the diagnostic process and to support plant operation and management: the loss of production, due to gas turbine deterioration, was identified