FUSION OF GAS TURBINES DIAGNOSTIC INFERENCE – THE DEMPSTER-SCHAFER APPROACH

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- The problem of engine fault diagnosis
- Description of the diagnostic procedure
  - General Overview
  - The method of BBN for fault diagnosis
  - The method of PNN for fault diagnosis
  - The Dempster-Schafer combination rule
- Method implementation
  - Diagnosis of thermodynamic faults on a turbofan engine
  - Diagnosis of mechanical faults from fast response data
- Summary - Conclusions

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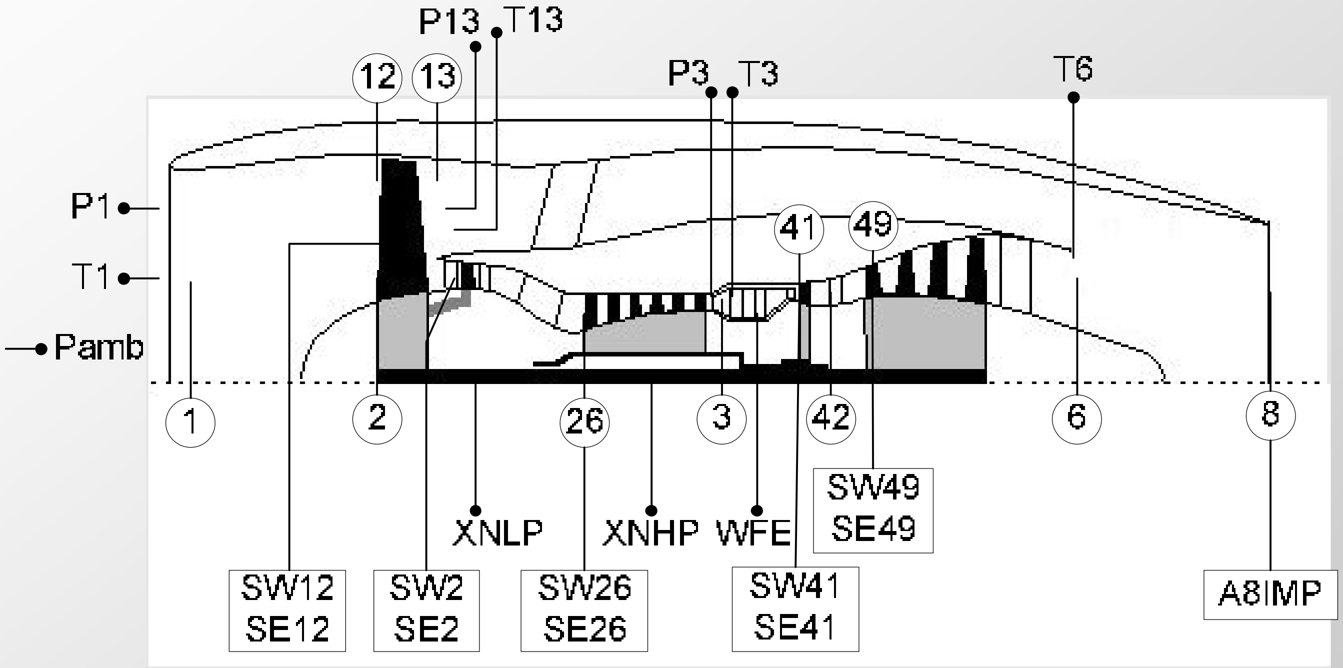
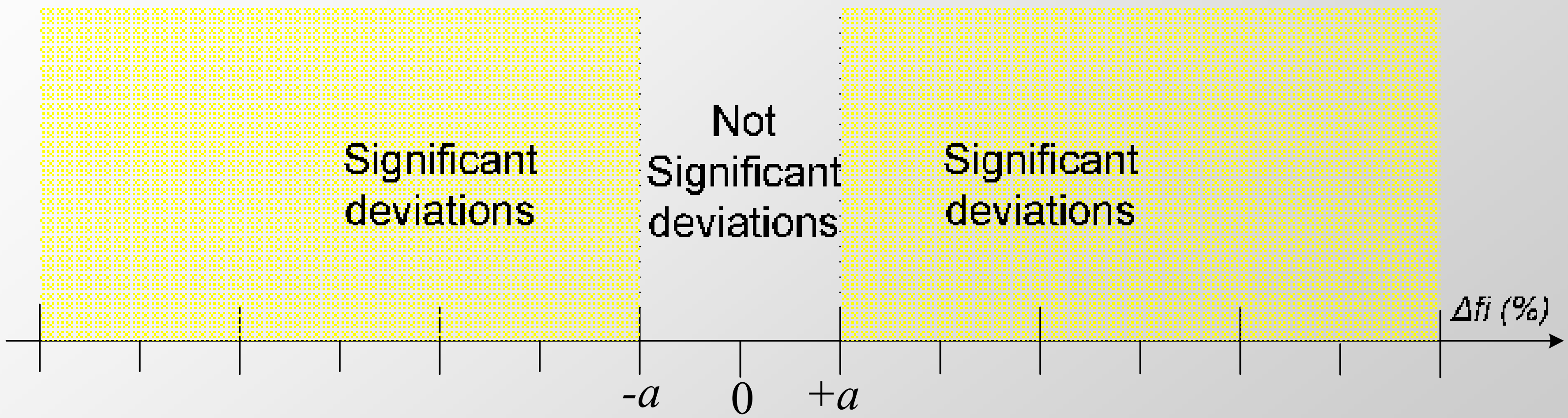
The problem of gas turbines fault diagnosis



High-by-Pass ratio, partially mixed, turbofan engine used as a test case

The problem of gas turbines fault diagnosis



Engine faults cause significant deviations on corresponding health parameters

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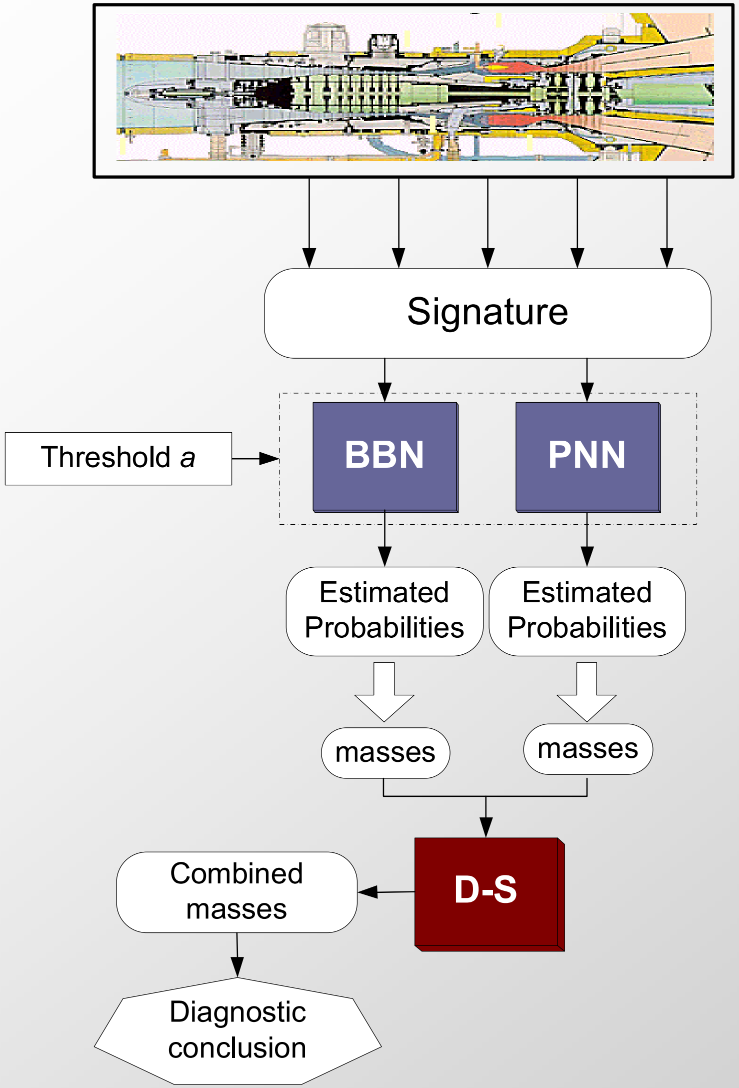
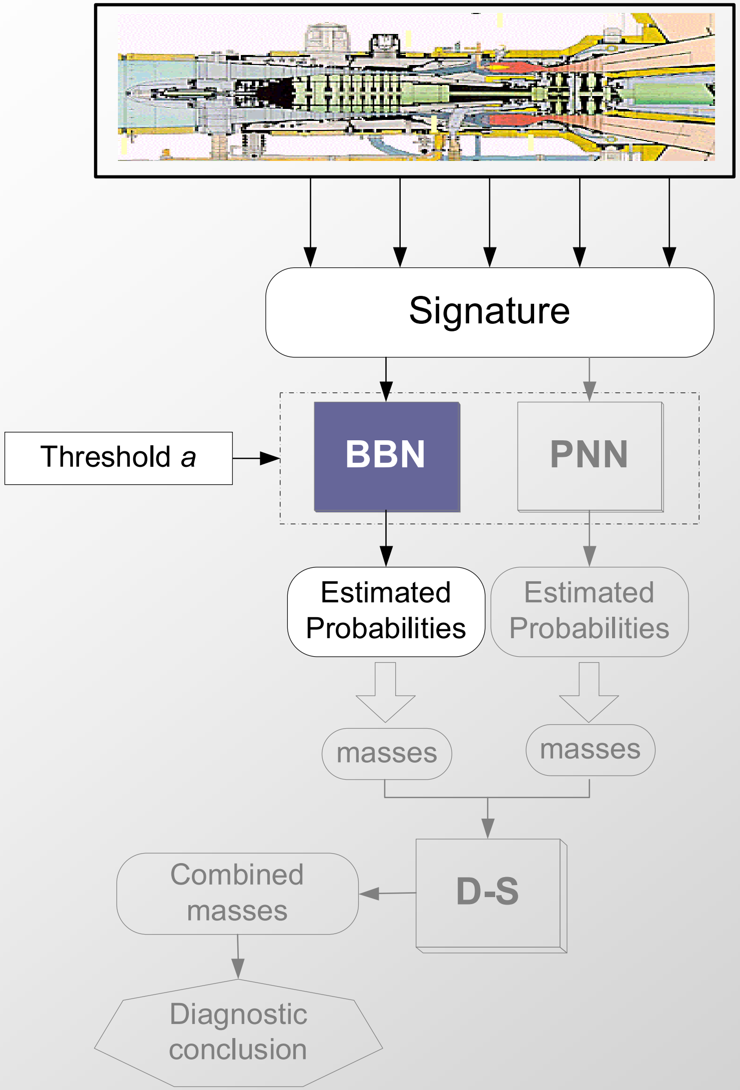
General overview of the proposed method



Diagnostic results from the methods of BBN and PNN are fused using of the Dempster-Schafer theory

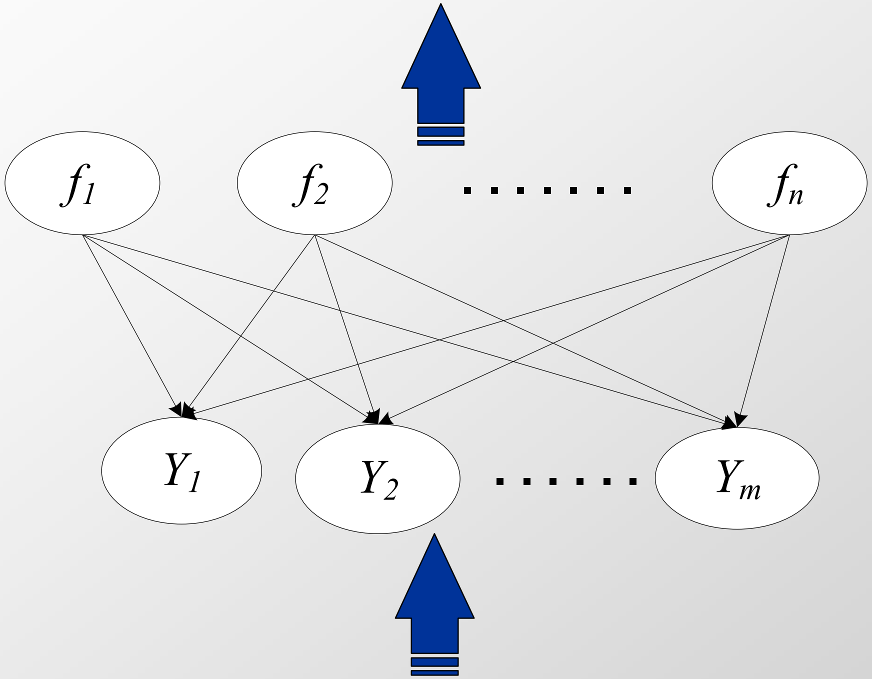


The method of BBN

The method of BBN estimates the probabilities for each health parameter to deviate due to a fault

The method of BBN for Gas Turbine fault diagnosis

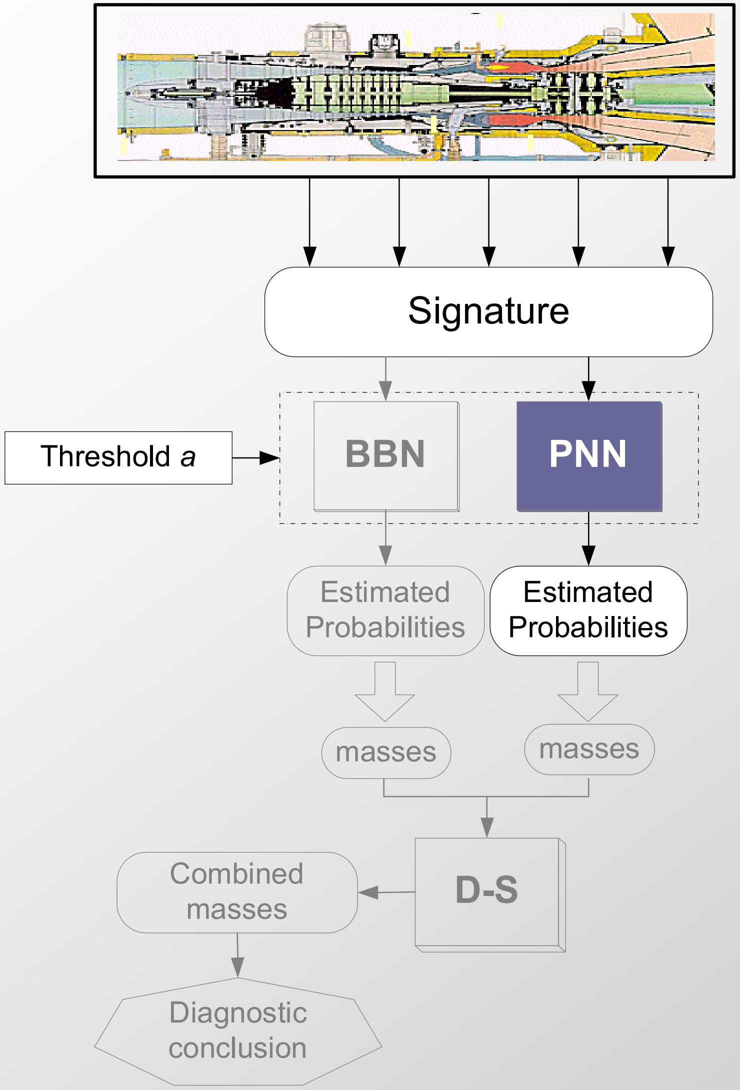
$P(\Delta f_i \notin [-\alpha, +\alpha] \mid Y_1, Y_2, \ldots, Y_m)$



$Y_1, Y_2, \ldots, Y_m$

For each health parameter f_i, the BBN estimates its probability to significantly deviate, given a set of measurements $Y_1, Y_2, \ldots, Y_m$

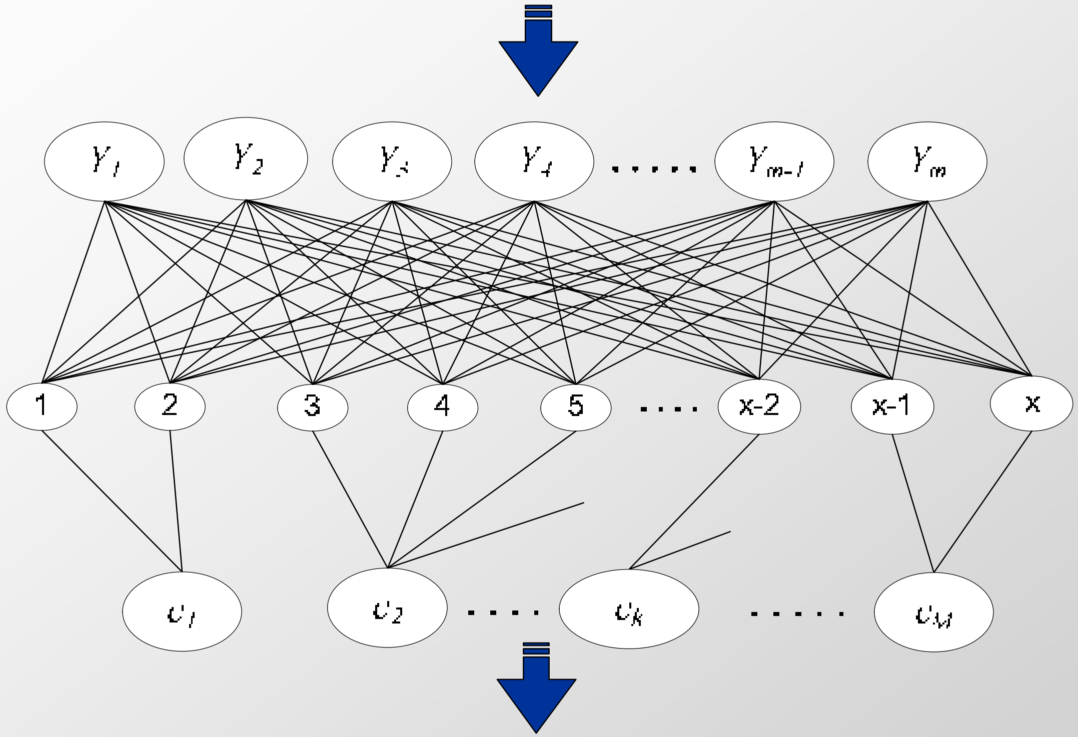
The method of PNN



The method of PNN allows a probabilistic classification among the health parameters that may deviate due to a fault

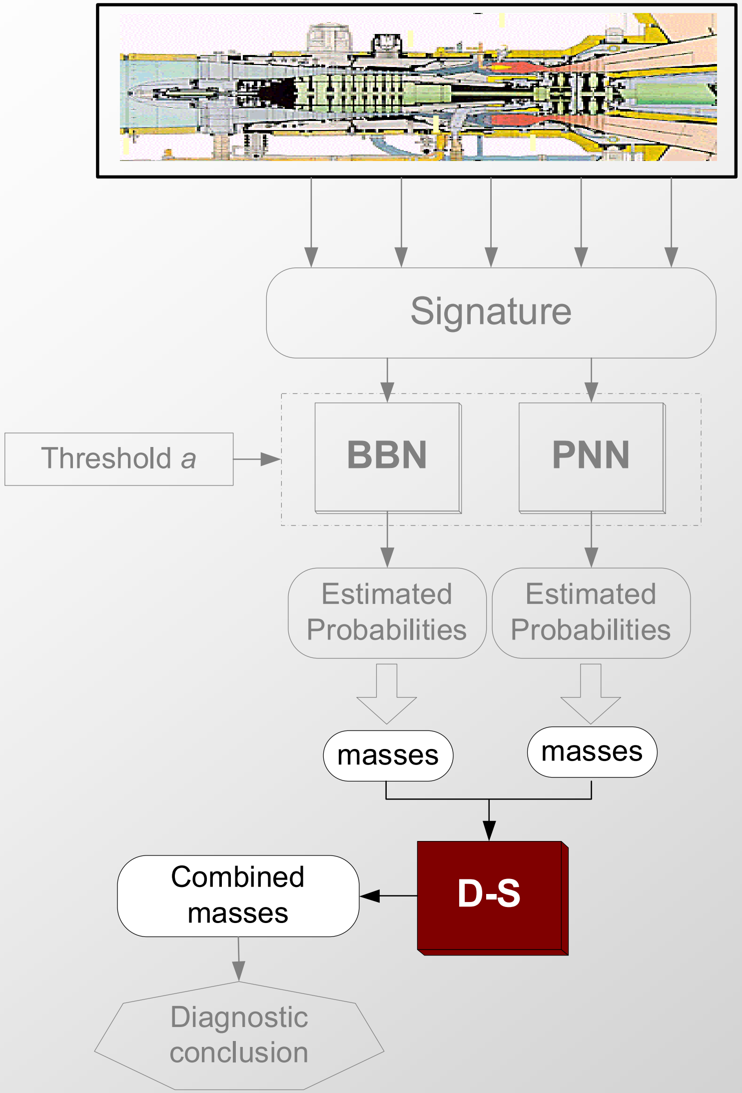
The method of PNN for Gas Turbine fault diagnosis

$Y_1, Y_2, \ldots, Y_m$



For each group of health parameter $c_k=\{f_i,\ldots, f_j\}$ the PNN estimates their probability to significantly deviate, given a set of measurements $Y_1, Y_2, \ldots, Y_m$

$$P(c_k=\{f_i, .., f_j\} \notin [-\alpha, +\alpha] \mid Y_1, Y_2, \ldots, Y_m)$$



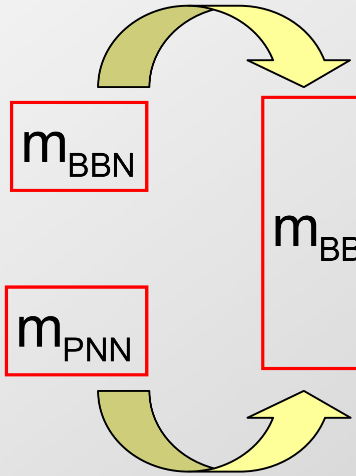
Fusion with Dempster-Schafer

The Dempster-Schafer theory combines the estimations of BBN and PNN into a ‘common belief’ measure for the health parameters’ deviation

Basic Principles of Dempster-Schafer theory

Dempster–Schafer theory: $m : \Theta \rightarrow [0,1], \mu\varepsilon\ m(\varnothing) = 0\ \kappa\alpha\iota \sum_{x \in \Theta} m(x)$

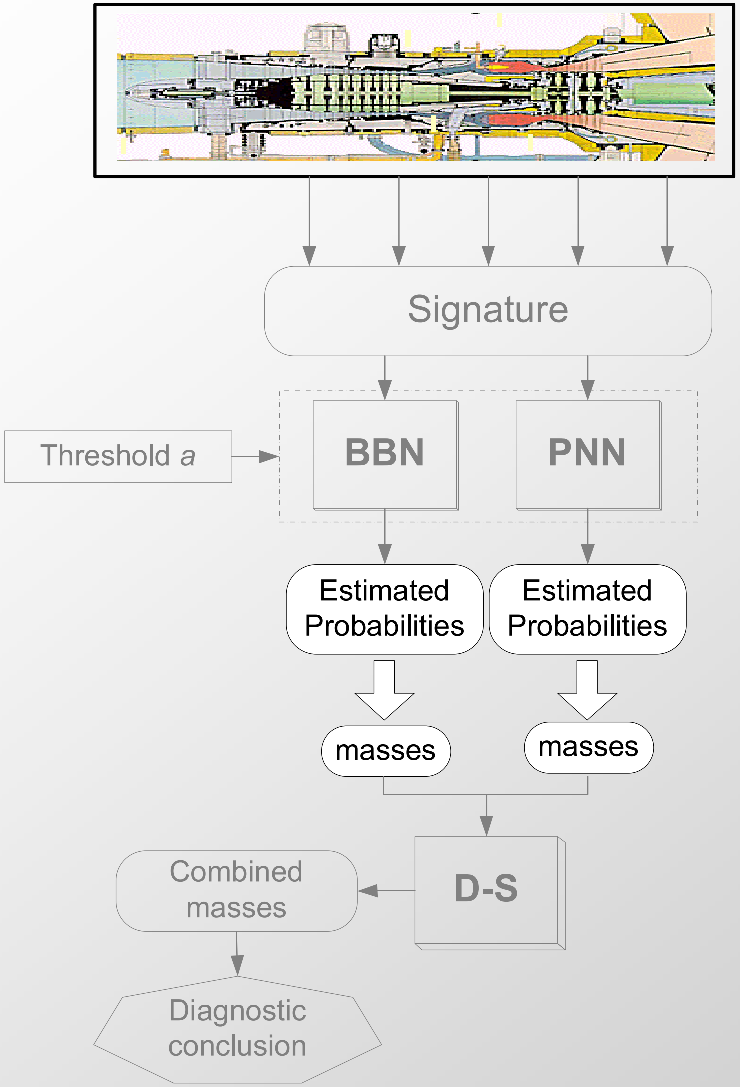
Probability theory: $P : \delta \rightarrow [0,1], \mu\varepsilon\ P(\varnothing) = 0\ \kappa\alpha\iota \sum_{x \in \delta} P(x)$



Dempster combination rule

$$m_{BBN} \oplus m_{PNN}(x) = \frac{\sum_{x_1 \cap x_2 = x} m_{BBN}(x_1) \cdot m_{PNN}(x_2)}{1 - \sum_{y_1 \cap y_2 = \varnothing} m_{BBN}(y_1) \cdot m_{PNN}(y_2)}$$

Transformation of probabilities



The output probabilities of BBN and PNN must be expressed in terms of 'masses' as these are defined in D-S theory

Transformation of probabilities

For a set of parameters, e.g. $x=\{f_i, f_j\}$,

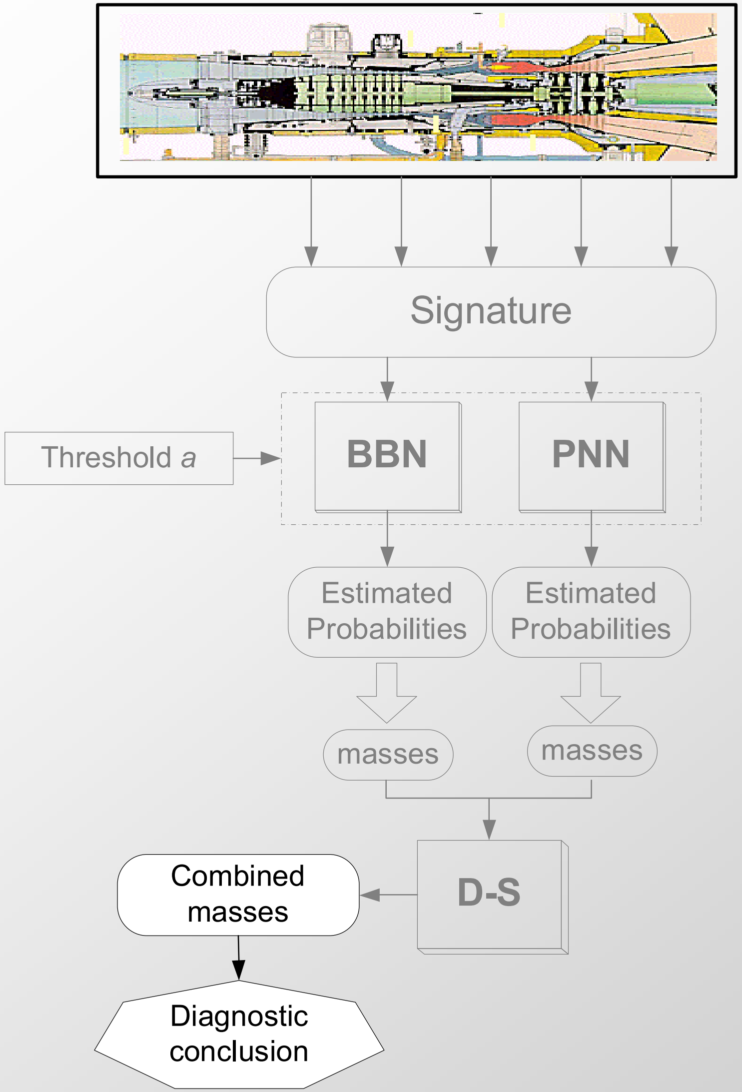
the mass represents the probability this set of parameters deviates significantly

$$m(x) = P\left(\Delta f_i \notin [-\alpha, +\alpha], \Delta f_j \notin [-\alpha, +\alpha]\right)$$

- $m_{BBN}(x) = P\left(\Delta f_i \notin [-\alpha, +\alpha] \| \boldsymbol{Y}\right) \cdot P\left(\Delta f_j \notin [-\alpha, +\alpha] \| \boldsymbol{Y}\right) \cdot P\left(\Delta f_k \in [-\alpha, +\alpha] \| \boldsymbol{Y}\right) \cdots$

- $m_{PNN}(x) = P\left(\Delta f_i \notin [-\alpha, +\alpha], \Delta f_j \notin [-\alpha, +\alpha] \| \boldsymbol{Y}\right)$

Extraction of diagnostic conclusions



The combined masses lead us to the final diagnostic conclusion by set of an appropriate criterion

$$m_{BBN} \oplus m_{PNN}(x_o) > m_{BBN} \oplus m_{PNN}(x)$$

"The set of parameters x_o with the max. value of combined mass deviate due to fault"

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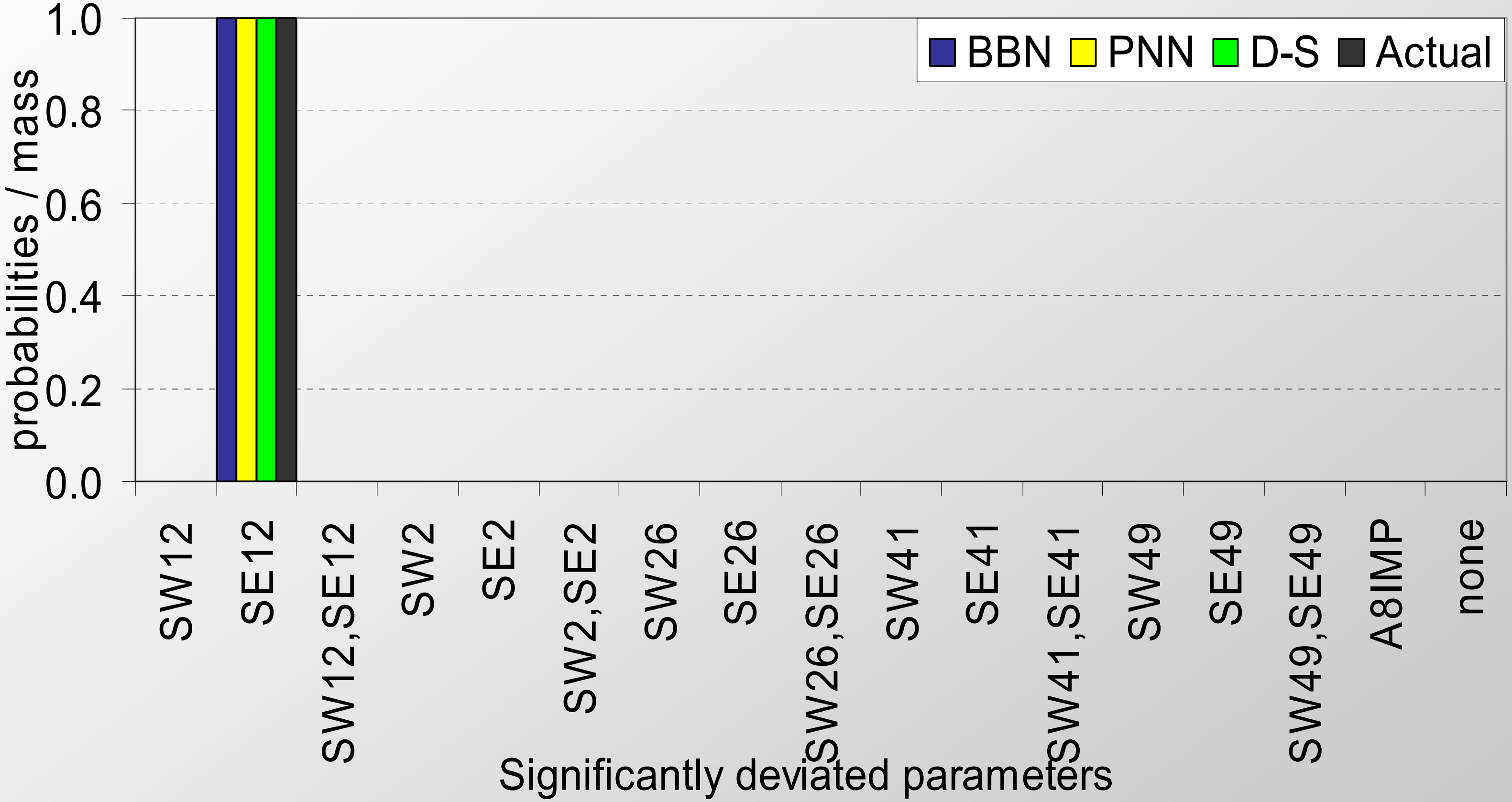
Method Implementation on a turbofan engine

fault case	actually deviated parameters	Parameters found to significantly deviate		
		BBN	PNN	D-S
a	SW2= -0.7%, SE2= -0.4%, SW12= -1%, SE12= -0.5%	SW12	SW12, SE12	SW12
b	SE12= -1%	SE12	SE12	SE12
c	SW26= -1%, SE26= -0.7%	SE26	SW26, SE26	SE26
d	SE26= -1%	SE26	SE26	SE26
e	SW26= -1%	SW26	SW26	SW26
f	SW41=+1%	SW41	SW41	SW41
g	SW41= -1%, SE41= -1%	SW41,SE41	SW41, SE41	SW41, SE41
h	SE41= -1%	SE41	SW49, SE49	SE41
i	SE49= -1%	SE49	SE49	SE49
j	SW49= -1%, SE49= -0.4%	SE41	SW49, SE49	SW49, SE49
k	SW49= -1%	SW49	SW49	SW49
l	SW49=+1%, SE49= -0.6%	SW49,SE49	SW49, SE49	SW49,SE49
m	A8IMP=+1%	A8IMP	A8IMP	A8IMP
n	A8IMP= -1%	A8IMP	A8IMP	A8IMP
o	A8IMP=+2%	A8IMP	A8IMP	A8IMP

15 benchmark fault cases have been examined.
Overall, the use of D-S fusion led to an improvement of diagnosis

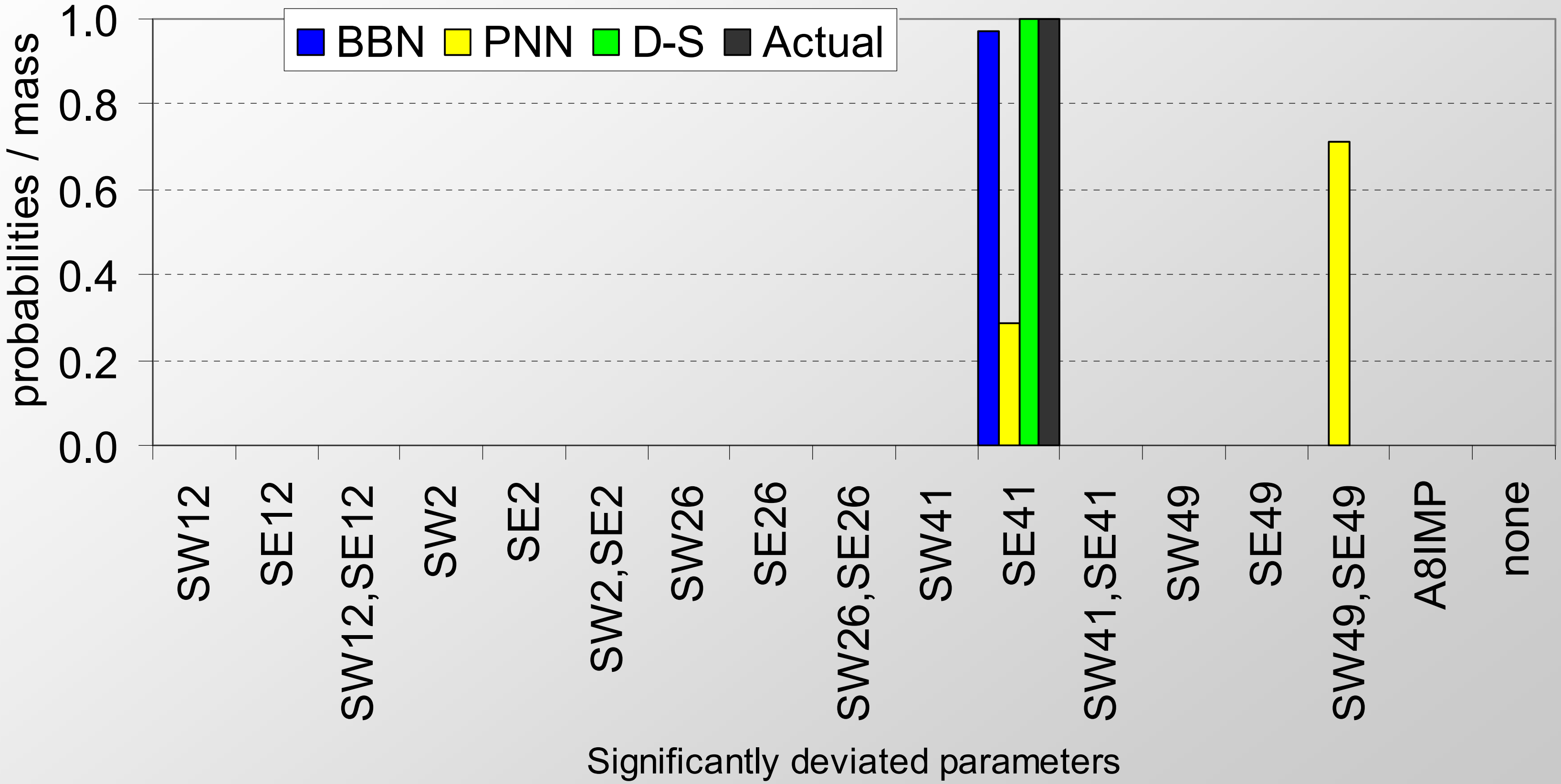
Method Implementation on a turbofan engine



‘b’ fault case: Both BBN and PNN methods detect correctly the existing fault.

Fusion with D-S also leads to a correct diagnosis.

Method Implementation on a turbofan engine



'h' fault case: Only the BBN method detects correctly the existing fault.

Fusion with D-S leads to a correct diagnosis.

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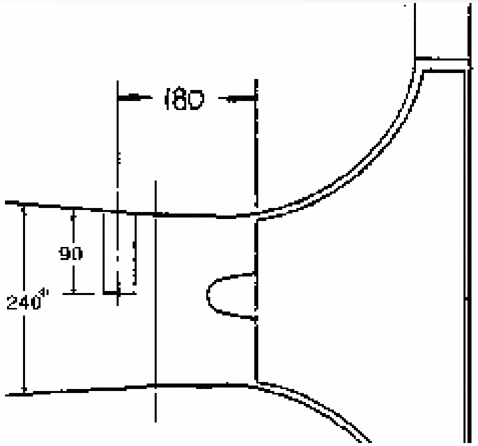
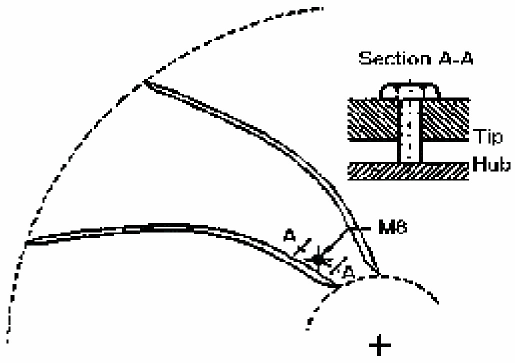
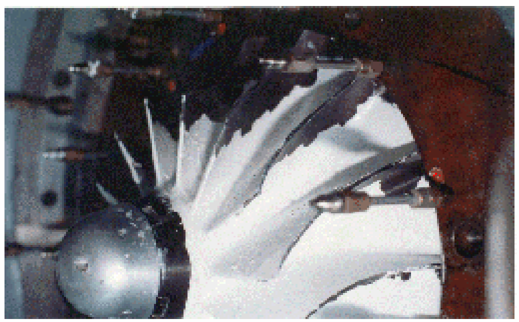
Examined Faults: Radial Compressor



Inlet Distortion-M3

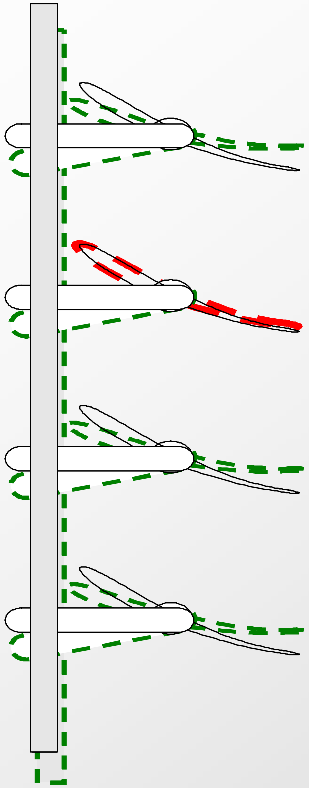


Diffuser Fault-M1



Impeller Fouling-M2

Examined Faults: Axial Compressor

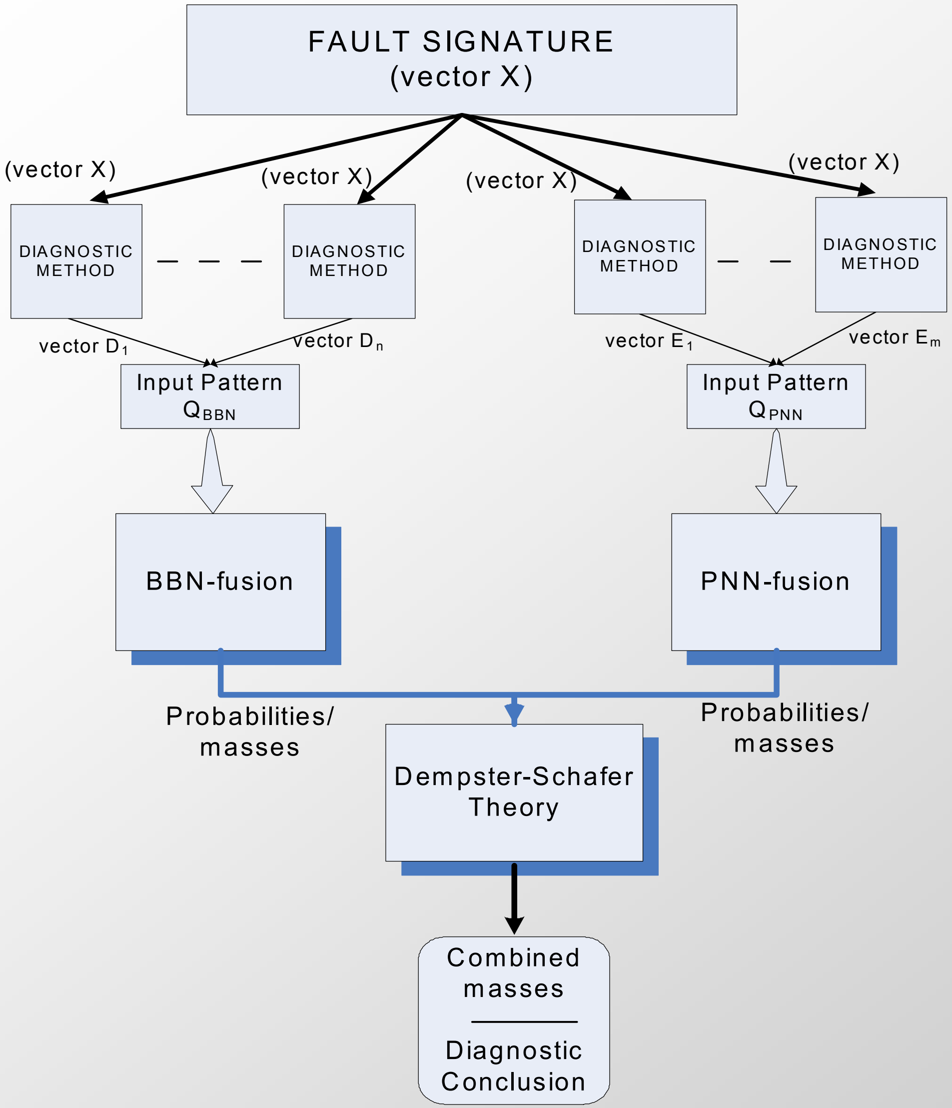


Fault 4

Fault 3

- **Fault 1: Severe Rotor Fouling**
- **Fault 2: Slight Rotor Blade Fault**
- **Fault 3: Severe Rotor Blade Fault**
- **Fault 4: Severe Stator Fault**

General overview of the proposed method for fast response data



- -BBN network
- -PNN network

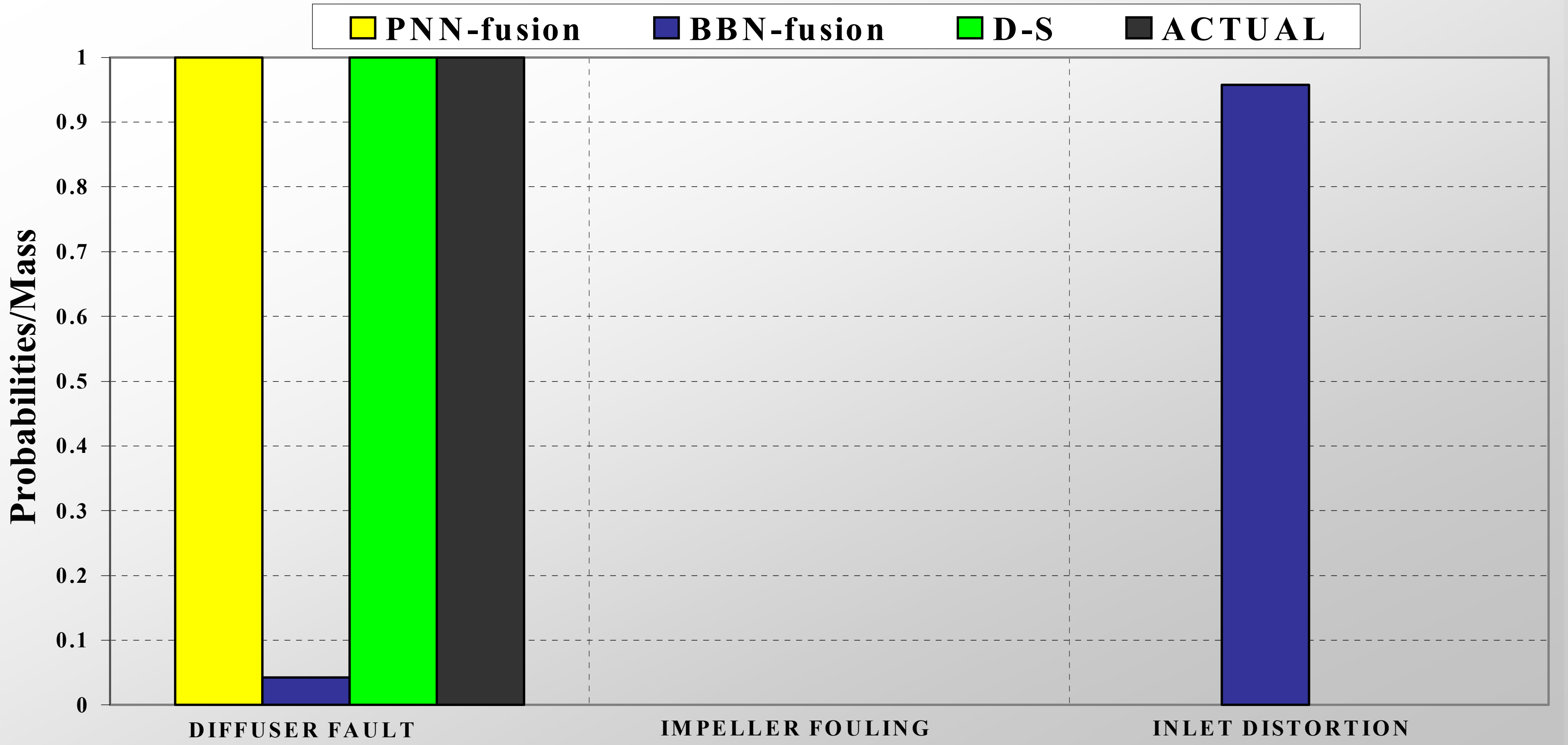
→ **appropriately modified**

Method Implementation on fast response data (radial and axial compressor)

Test-rigs	Instruments	Number of incorrect classifications		
		BBN-fusion	PNN-fusion	D-S
Radial	Microphones	2/24	1/24	1/24
Axial	ACC1	1/16	1/16	1/16
-//-	ACC2	0/16	0/16	0/16
-//-	ACC3	0/16	0/16	0/16
-//-	PT-2	0/16	1/16	0/16
-//-	Mic-1	0/16	0/16	0/16

test-cases of incorrect classification/total test-cases

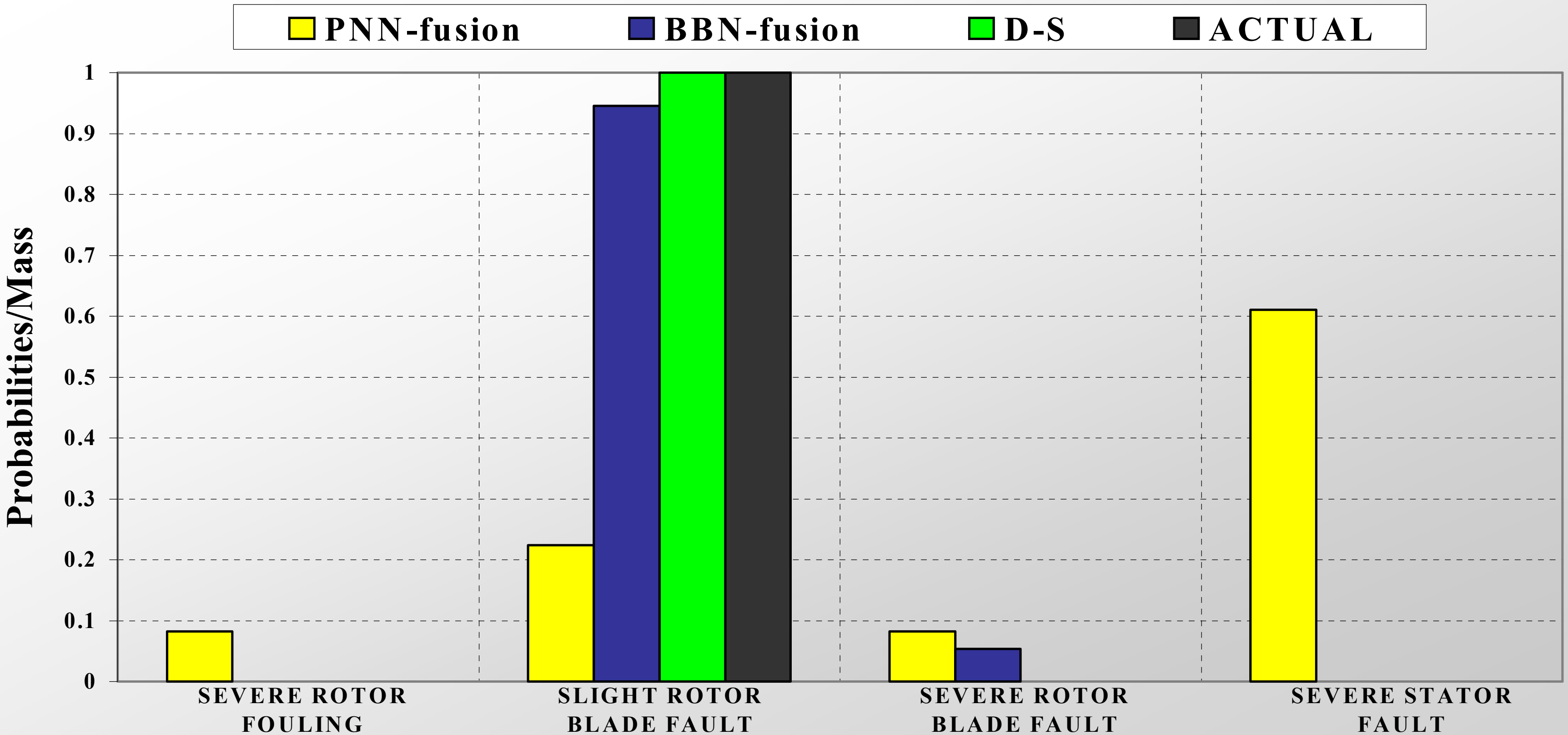
Method Implementation on fast response data (radial)



Test case 2: Only the PNN-fusion method detects correctly the existing fault.

Fusion with D-S leads to a correct diagnosis.

Method Implementation on fast response data (axial)



Test case 7: Only the BBN-fusion method detects correctly the existing fault.

Fusion with D-S leads to a correct diagnosis.

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Summary - Conclusions

- A diagnostic procedure combining two individual methods and a fusion technique has been presented. The method combines the output probabilities of a BBN and a PNN through the principles of Dempster-Schafer theory.
- The case of a turbofan engine has been examined. In that case the proposed method has been applied for the diagnosis of 15 benchmark fault cases from aerothermodynamic data.
- The case of an axial and a radial compressor has also been examined. In both compressors the proposed method has been applied for the diagnosis of mechanical faults from fast response data.
- In all examined cases, fusion of the results of individual methods led to an improvement of diagnosis