GAS TURBINES DIAGNOSTICS USING WEIGHTED PARALLEL DECISION FUSION FRAMEWORK

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- Development of the fusion procedure
- Description-Details of the fusion procedure
  - o Definition and construction of weights
  - o Weighting application variants
  - o BBN-fusion architecture
  - o Decision criterion
- Application of the method- Results
  - o Diagnosis of component faults on a turbofan engine
    1. Individual diagnostic methods
    2. Fusion Procedure
  - o Diagnosis of mechanical faults in a radial compressor
    1. Individual diagnostic methods
    2. Fusion Procedure
- Summary - Conclusions

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Development of the fusion procedure

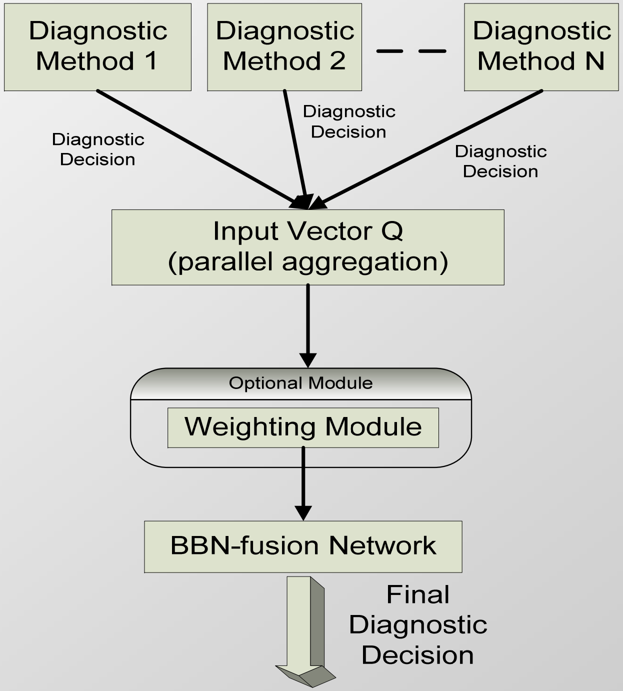
- Independent diagnostic methods are considered, which derive diagnostic decisions.
- The developed fusion procedure models diagnostic decisions as vectors of probabilities.
- The decisions are fused in parallel forming a concatenating vector ***Q***.
- Each vector $q^i(j)$ is comprised of 0 (zeros) and a 1 (unity) corresponding to the diagnostic decision regarding an independent diagnostic method.

$$\mathbf{Q}^i(j) = \begin{cases} q^1(j), & j = 1, \dots, M \\ q^2(j), & j = (M+1), \dots, 2 \cdot M \\ q^3(j), & j = (2 \cdot M + 1), \dots, 3 \cdot M \\ \dots\dots & \\ \dots\dots & \\ q^N(j), & j = [(N-1) \cdot M + 1], \dots, N \cdot M \end{cases}$$

$$q^i(j) = \begin{cases} 1, & j = m \\ 0, & j = 1, 2, \dots, m-1, m+1, \dots M \end{cases}$$

Development of the fusion procedure

- The vector ***Q*** is fed to a weighting module (optional).
- The transformed ***Q*** is input to a Bayesian Belief Network (BBN).
- The output of the BBN based on a decision criterion derives the final diagnostic decision.



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WEIGHT DEFINITION

Why weighting?

- **Weighting application quantifies usage experience, credibility, a priori knowledge etc.**
- **Has mathematical base (derived from statistics).**
- **Ease in implementation.**

Two different approaches for weight definition:

- **"Optimistic" approach**
- **"Pessimistic" approach**

For the purposes of the current work the "pessimistic" approach for weight definition was adopted

Two different approaches for weight definition:

- **"Optimistic" approach**

The weights of each diagnostic method are defined indirectly by comparing its effectiveness to the effectiveness of all other methods.

- **Efficiency (e) is defined as : K_{Wrong} (number of incorrect classifications)**
- **The least effective method *i* is assigned a weight vector Wi = (1, 1,…, 1)**
- **Every other method *j* is assigned a weight vector equal to :** $e = \frac{K^{i}_{Wrong}}{K^{j}_{Wrong}}$

e.g. If a diagnostic method1 misses 4 examined fault cases and diagnostic method2 misses 2 then:

$$K^{1}_{Wrong} = 4 \quad K^{2}_{Wrong} = 2 \quad e = \frac{K^{1}_{Wrong}}{K^{2}_{Wrong}} = 2 \quad W_1 = (1, 1, ..., 1) \ and \ W_2 = (2, 2, ..., 2)$$

Two different approaches for weight definition:

- **"Pessimistic" approach**

The weights (of each diagnostic method) are defined according to its efficiency.

- **Efficiency (e) is defined as the quotient:** $$e = \frac{K_{Correct}}{K_{Total}}$$

$K_{Correct}$: number of correctly classified test-cases

K_{Total} : total number of test-cases

e.g. If a diagnostic method *i* has an efficiency e = 80%

then its weight vector is: *Wi = (0.8, 0.8,…,0.8).*

WEIGHTING APPLICATION VARIANTS

Weight Vectors *W* are applied upon the diagnostic decisions vectors *Q*

The number of elements of the Weight Vectors *W*

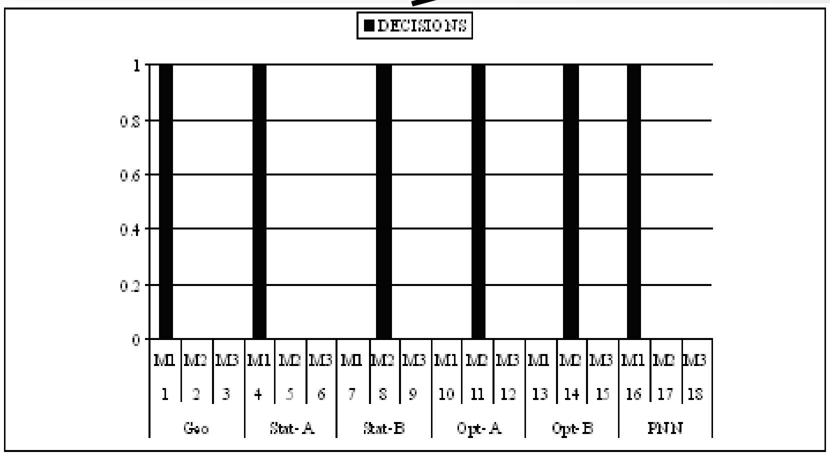
are equal to the number of examined fault classes

Two different weighting application variants have been developed:

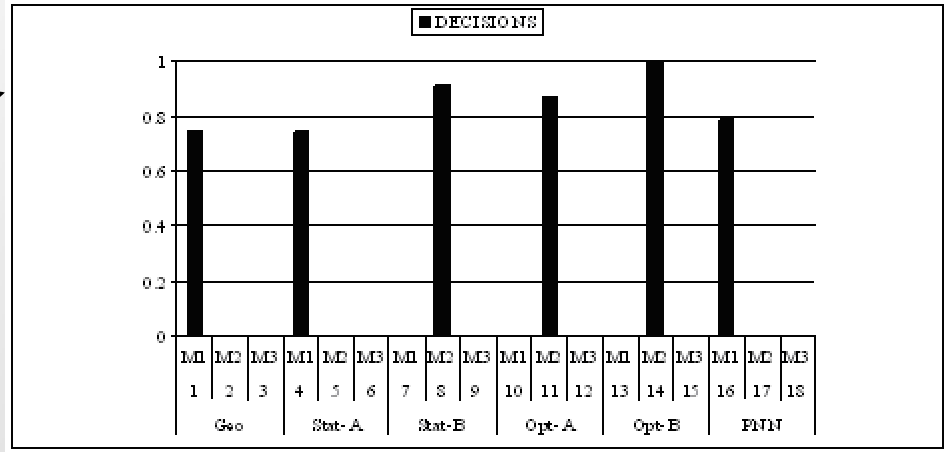
PlWe: **Weight vectors *Wi* are applied directly (multiplied) upon vector *Q,* regarding each diagnostic method.**

WeRd: **Weight vectors *Wi* are applied directly (multiplied) upon the unity values of Q. The quantity derived by *1-Wi* is uniformly redistributed to the other fault classes regarding each diagnostic method, altering thus its zero values.**

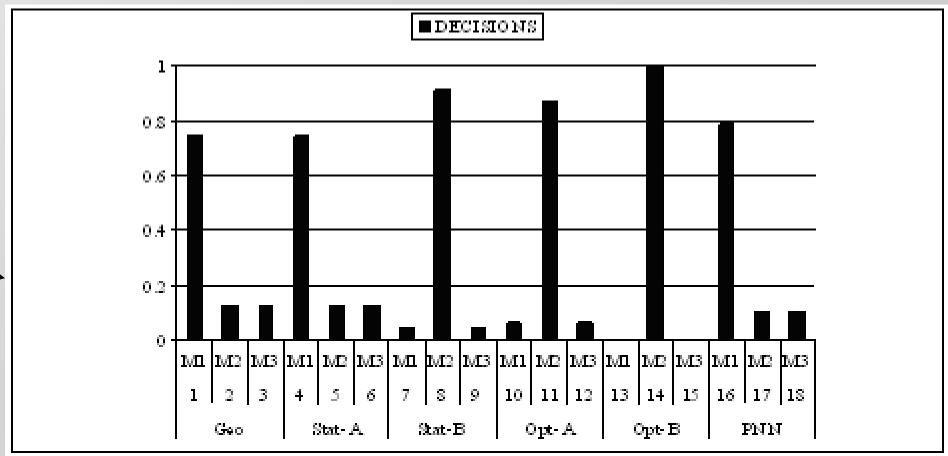
WEIGHTING APPLICATION VARIANTS



PlWe



WeRd



BBN-fusion ARCHITECTURE

Elements of BBN-fusion network

•NODES:

- **‘Root’ (or fault) nodes represent the fault classes (elements of vector *F*).**
- **‘Leaf’ (or child) nodes represent diagnostic decisions (elements of vector *Q*).**

•LINKS:

Fully linked network

•BAYESIAN INFERENCE:

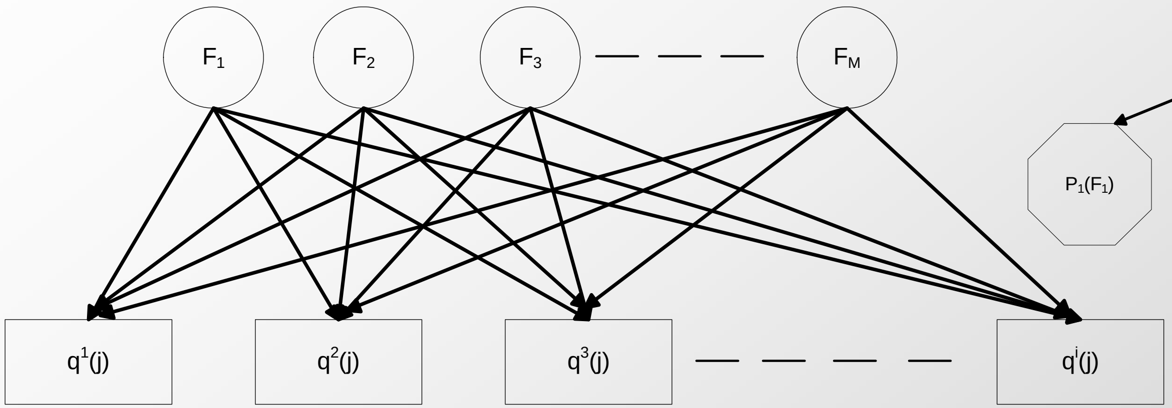
According to probabilistic relationship: $P[Q(1),...,Q(N*M),F1,...FM]=\prod_{i=1}^{M}P(Fi)\prod_{j=1}^{N*M}P[Q(j)|F1,...,FM]$

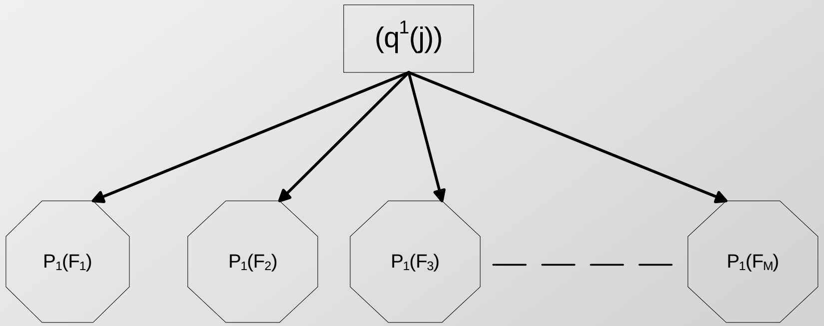
•DISCRETE STATES AND CONDITIONAL PROBABILITY TABLES (CPT) OF ‘FAULT’ NODES:

•5 discrete states forming intervals of interest (probability of fault occurrence).

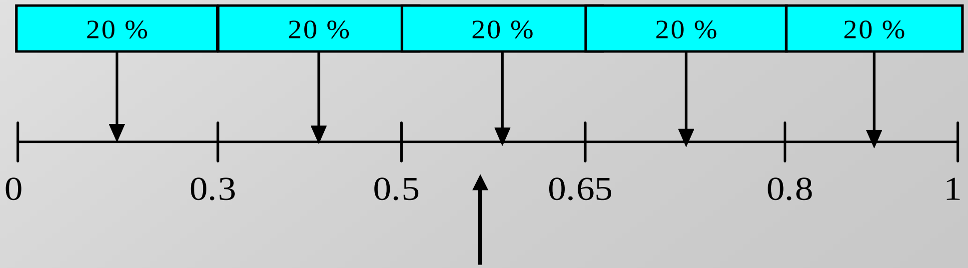
•CPT table contains a-priori probability (uniform distribution).

BBN-fusion ARCHITECTURE





F_j : j^{th} Examined fault class
$q^i(j)$: Probability vector about fault class by diagnostic method ***i***



States of a ‘fault’ node (intervals of interest) and a-priori probabilities

DECISION CRITERION

Decision Criterion is realized in two steps:

1. **Interval [0.8-1] is examined. Vector *Q* is classified to fault class X according to:**

$$P[Fi = X \mid Q(1),...,Q(N*M)] = \max_{i=1}^{M}\{P[Fi = X \mid Q(1),...,Q(N*M)]\}$$

2. **If [0.8-1] is zero for all fault nodes a N/A is returned and step 2 (“soft version”) examines preceding intervals sequentially following above relation.**

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The case of a turbofan engine for the diagnosis of 15 benchmark fault cases from aerothermodynamic data, has been examined.

Diagnostic Methods : 1. Combinatorial Approach (CMBN or Comb)

2. Non-Linear Least Squares Optimization (NLOpt(LS))

3. Bayesian Belief Network (BBN)

4.Engine Partitioning (LHN)

5. Engine Partitioning (CHN)

- As a first fusion application all methods are fused together.
- As second application 5 different combinations of them are fused, which are:

CHN-LHN-CMBN, CHN-LHN-BBN, CHN-LHN-CMBN-BBN,

CHN-LHN-NLOpt(LS), CMBN-NLOpt(LS)-BBN

Turbofan engine benchmark fault cases.

Fault Cases	Actual Faults	CMBN	NLOpt(LS)	BBN	CHN	LHN
A	FANLPC	FANLPC	FANLPC	FANLPC NOZZLE	~~HPT~~	FANLPC
B	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC
C	HPC	~~FANLPC~~	~~FANLPC~~	~~FANLPC~~	HPC	HPC
D	HPC	HPC	HPC	HPC	HPC	HPC
E	HPC	HPC	HPC	HPC	HPC	~~FANLPC~~
F	HPT	HPT	HPT	HPT	HPT	HPT
G	HPT	HPT	HPT	HPT	HPT	HPT
H	HPT	HPT	HPT	HPT	HPT	HPT
I	LPT	LPT	LPT	LPT	LPT	LPT
J	LPT	~~FANLPC~~	~~HPT~~	~~N/A~~	~~HPT~~	LPT
K	LPT	~~FANLPC~~	~~HPT~~	LPT	LPT	~~FANLPC~~
L	LPT	LPT	~~HPT~~	LPT	LPT	LPT
M	NOZZLE	~~FANLPC~~	NOZZLE	NOZZLE	NOZZLE	~~HPC~~
N	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE	~~FANLPC~~
O	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE

Results from independent diagnostic methods.

Turbofan engine benchmark fault cases.

		First Decision Step ("strict")			Second Decision Step ("soft")		
Fault Cases	Actual Faults	No weights	PlWe	WeRd	No weights	PlWe	WeRd
A	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC
B	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC	FANLPC
C	HPC	~~FANLPC~~	~~N/A~~	~~N/A~~	~~FANLPC~~	~~FANLPC~~	~~FANLPC~~
D	HPC	HPC	HPC	HPC	HPC	HPC	HPC
E	HPC	HPC	HPC	HPC	HPC	HPC	HPC
F	HPT	HPT	HPT	HPT	HPT	HPT	HPT
G	HPT	HPT	HPT	HPT	HPT	HPT	HPT
H	HPT	HPT	HPT	HPT	HPT	HPT	HPT
I	LPT	LPT	LPT	LPT	LPT	LPT	LPT
J	LPT	~~HPT~~	~~N/A~~	~~N/A~~	~~HPT~~	~~HPT~~	~~HPT~~
K	LPT	FANLPC LPT	~~N/A~~	~~N/A~~	FANLPC LPT	FANLPC LPT	LPT
L	LPT	LPT	LPT	LPT	LPT	LPT	LPT
M	NOZZLE	NOZZLE	~~N/A~~	~~N/A~~	NOZZLE	NOZZLE	NOZZLE
N	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE
O	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE	NOZZLE

Results from fusing

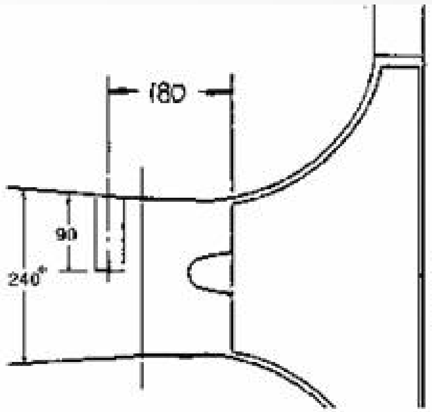
all diagnostic methods' decisions

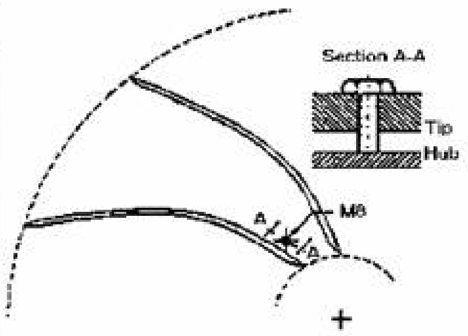
Turbofan engine benchmark fault cases.

Considered Combinations	First Decision Step ("strict") No weights		First Decision Step ("strict") PlWe	First Decision Step ("strict") WeRd	Second Decision Step ("soft") No weights		Second Decision Step ("soft") PlWe		Second Decision Step ("soft") WeRd
CHN-LHN-CMBN	K	J,M	J,K,M	J,K,M	K	J,M	K	J,M	J,K
CHN-LHN-BBN	---	J	J	J	---	J	---	J	J
CHN-LHN-CMBN-BBN	J	C,K	C,J,K,M	C,J,K,M	---	C,J,K	---	C,J,K	J
CHN-LHN-NLOpt(LS)	J	K	J,K	J,K	J	K	J	K	J
CMBN-NLOpt(LS)-BBN	C,J	K	C,J,K	C,J,K	C,J	K	C,J	K	C,J

Results from fusing considered combinations of diagnostic methods

Diagnosis of mechanical faults: The radial compressor case





Inlet Distortion-M3

Diffuser Fault-M1

Impeller Fouling-M2

Diagnosis of mechanical faults: The radial compressor case

Diagnostic Methods :
1. Geo: Geometrical Pattern Recognition.
2. Stat-A: Statistical Pattern Recognition with feature vector A.
3. Stat-B: Statistical Pattern Recognition, same as 2 but now with feature vector B.
4. Opt-A: Statistical with Optimal Directions Pattern Recognition with feature vector A.
5. Opt-B: Statistical with Optimal Directions Pattern Recognition, same as 4 but now with feature vector B.
6. PNN: Probabilistic Neural Network.

- **As a first fusion application all methods are fused together.**
- **As second application 3 different combinations of them are fused, which are:**

1-3-5, 3-4-5, 3-4-5-6

Radial Compressor fault cases.

No. of Test-Case	Real Faults	Geo	Stat-A	Stat-B	Opt-A	Opt-B	PNN
1	M1	M1	M1	M1	M1	M1	M1
2	M1	~~M3~~	~~M3~~	M1	~~M3~~	M1	~~M3~~
3	M1	M1	~~M3~~	~~M3~~	M1	M1	M1
4	M1	M1	M1	M1	M1	M1	M1
5	M1	~~M3~~	M1	M1	M1	M1	M1
6	M1	M1	M1	M1	M1	M1	M1
7	M1	M1	M1	M1	M1	M1	M1
8	M1	M1	M1	M1	M1	M1	M1
9	M2	M2	M2	M2	M2	M2	M2
10	M2	~~M3~~	~~M3~~	M2	M2	M2	~~M3~~
11	M2	M2	M2	M2	M2	M2	M2
12	M2	M2	M2	M2	M2	M2	M2
13	M2	M2	M2	M2	M2	M2	M2
14	M2	M2	M2	M2	M2	M2	M2
15	M2	~~M1~~	~~M1~~	M2	M2	M2	~~M1~~
16	M2	~~M3~~	~~M3~~	M2	M2	M2	~~M3~~
17	M3	M3	M3	M3	M3	M3	M3
18	M3	M3	M3	M3	M3	M3	M3
19	M3	~~M1~~	~~M1~~	~~M1~~	~~M1~~	M3	~~M1~~
20	M3	M3	M3	M3	~~M1~~	M3	M3
21	M3	M3	M3	M3	M3	M3	M3
22	M3	M3	M3	M3	M3	M3	M3
23	M3	M3	M3	M3	M3	M3	M3
24	M3	M3	M3	M3	M3	M3	M3

Results from independent diagnostic methods.

Radial Compressor fault cases.

		First Decision Step (“strict”)			Second Decision Step (“soft”)		
No. Of Test-Case	Real Faults	No weights	PlWe	WeRd	No weights	PlWe	WeRd
1	M1	M1	M1	M1	M1	M1	M1
2	M1	~~M3~~	~~N/A~~	~~N/A~~	~~M3~~	M1	M1
3	M1	M1	M1	M1	M1	M1	M1
4	M1	M1	M1	M1	M1	M1	M1
5	M1	M1	M1	M1	M1	M1	M1
6	M1	M1	M1	M1	M1	M1	M1
7	M1	M1	M1	M1	M1	M1	M1
8	M1	M1	M1	M1	M1	M1	M1
9	M2	M2	M2	M2	M2	M2	M2
10	M2	M2, M3	M2	~~N/A~~	M2, M3	M2	M2
11	M2	M2	M2	M2	M2	M2	M2
12	M2	M2	M2	M2	M2	M2	M2
13	M2	M2	M2	M2	M2	M2	M2
14	M2	M2	M2	M2	M2	M2	M2
15	M2	M1, M2	M2	~~N/A~~	M1, M2	M2	M2
16	M2	M2, M3	M2	~~N/A~~	M2, M3	M2	M2
17	M3	M3	M3	M3	M3	M3	M3
18	M3	M3	M3	M3	M3	M3	M3
19	M3	~~M1~~	~~N/A~~	~~N/A~~	~~M1~~	~~M1~~	~~M2~~
20	M3	M3	M3	M3	M3	M3	M3
21	M3	M3	M3	M3	M3	M3	M3
22	M3	M3	M3	M3	M3	M3	M3
23	M3	M3	M3	M3	M3	M3	M3
24	M3	M3	M3	M3	M3	M3	M3

Results from fusing all diagnostic methods’ decisions

Radial Compressor fault cases.

Considered Combinations	First Decision Step ("strict") No weights		PlWe	WeRd	Second Decision Step ("soft") No weights		PlWe	WeRd
ALL	2/24	3/24	2/24	5/24	2/24	3/24	1/24	1/24
Methods1-3-5	1/24		0/24	0/24	1/24		0/24	0/24
Methods3-4-5	1/24		0/24	0/24	1/24		0/24	0/24
Methods3-4-5-6	2/24		1/24	1/24	2/24		1/24	0/24

Results from fusing considered combinations of diagnostic methods

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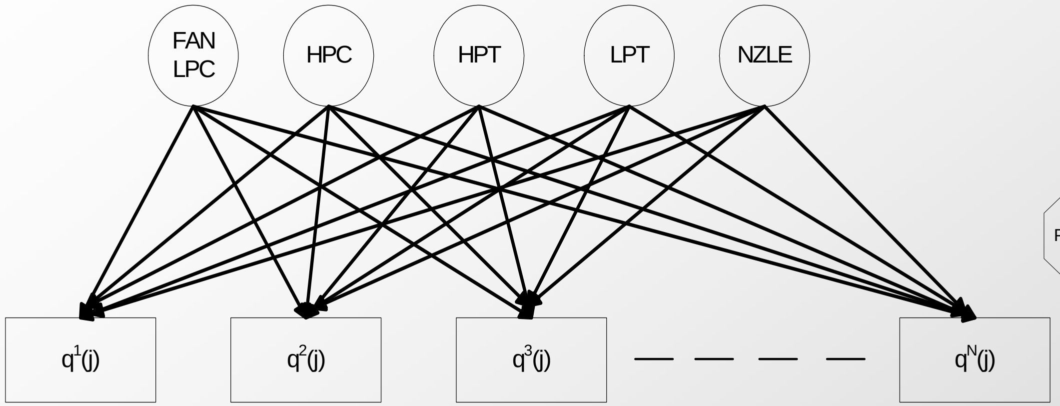
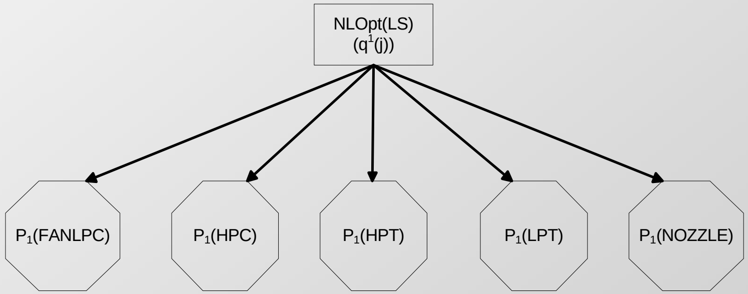
Summary - Conclusions

- **An approach for parallel decision fusion concerning gas turbines fault diagnosis has been presented, which utilizes a BBN network .**
- **A novel weighting module with two variants, that alters the input information to the BBN-fusion network has been developed.**
- **Effectiveness of the method has been demonstrated by application to two different diagnostic problems.**
- **It was proven that the proposed information fusion techniques led to an improvement of the final diagnostic decision.**
- **Also, the developed fusion method presents broad generality.**

i) It can be exploited for different fault scenarios as presented.

ii)It can utilize diagnostic methods with different sources of input data by interpreting their diagnostic outcomes into a common ground of probabilistic beliefs, which are the input vectors to the BBN-fusion network.

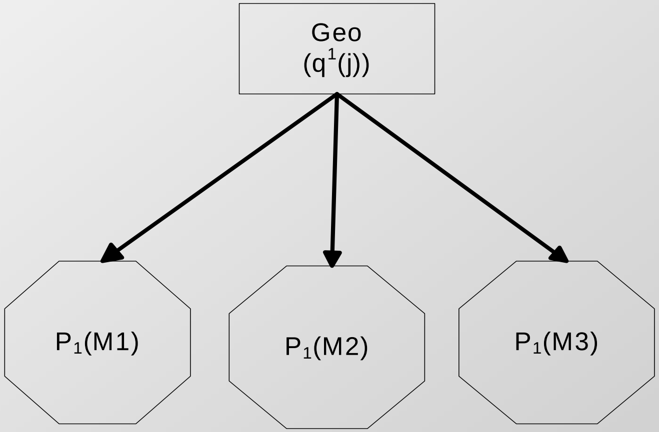


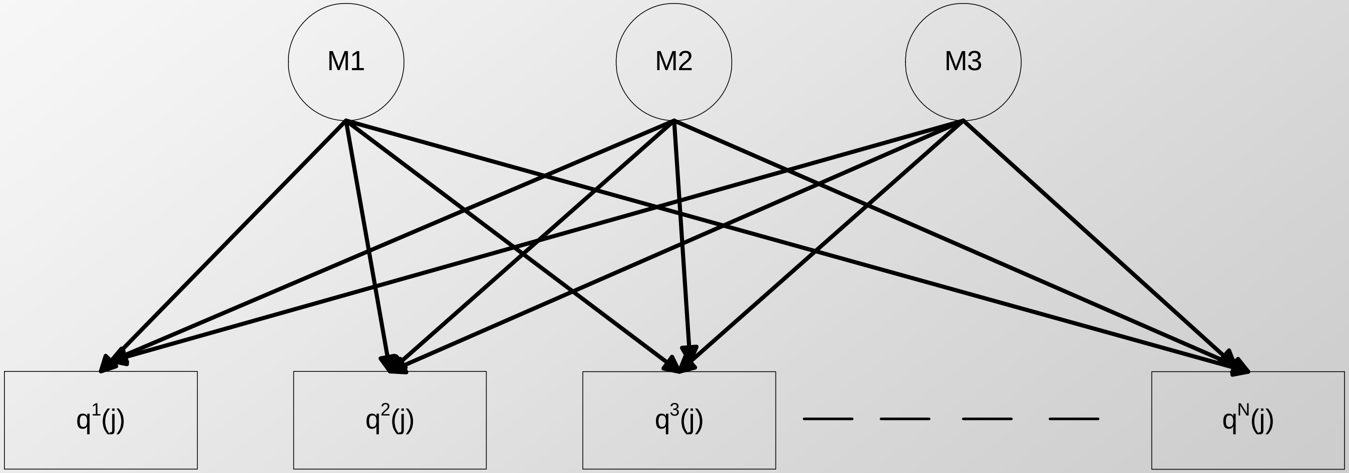


$q^i(j)$: Probability vector about faulty engine component by diagnostic method ***i***

$$Q^i(j) = \begin{cases} q^1(j), \quad j = 1, \ldots, M & \text{for } NLOpt(LS) \\ q^2(j), \quad j = (M+1), \ldots, 2 \cdot M & \text{for Combinatorial} \\ q^3(j), \quad j = (2 \cdot M+1), \ldots, 3 \cdot M & \text{for } CHN \\ q^4(j), \quad j = (3 \cdot M+1), \ldots, 4 \cdot M & \text{for } LHN \\ q^5(j), \quad j = (4 \cdot M+1), \ldots, 5 \cdot M & \text{for } BBN \end{cases}$$

$$Q^i(j) = \begin{cases} q^1(j), & j = 1, \dots, M & \text{for Geo} \\ q^2(j), & j = (M+1), \dots, 2 \cdot M & \text{for Stat} - A \\ q^3(j), & j = (2 \cdot M+1), \dots, 3 \cdot M & \text{for Stat} - B \\ q^4(j), & j = (3 \cdot M+1), \dots, 4 \cdot M & \text{for Opt} - A \\ q^5(j), & j = (4 \cdot M+1), \dots, 5 \cdot M & \text{for Opt} - B \\ q^6(j), & j = (5 \cdot M+1), \dots, 6 \cdot M & \text{for PNN} \end{cases}$$





$q^i(j)$: Probability vector about mechanical fault by diagnostic method ***i***