Technische Universität Braunschweig

IFAS Institut für Flugantriebe und Strömungsmaschinen

11. Dresdner Probabilistik-Workshop

10th – 11th October 2019

Forecasting the condition of high-pressure turbine parts by using Bayesian Belief Networks

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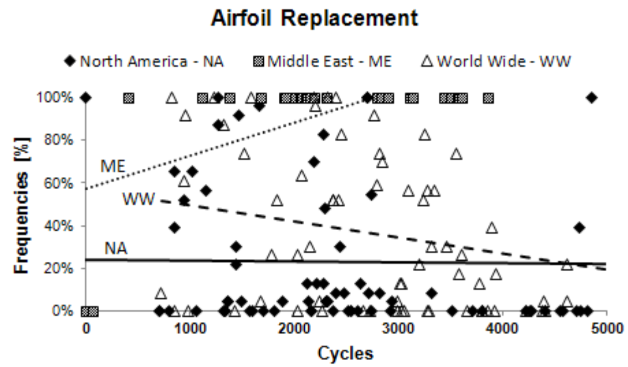
Content

1. Background
2. Aims/objectives & methodology
3. Construction of a Bayesian Belief Network (BBN)
4. Verification & evaluation
5. Conclusions

Why BBN?

- shop visits (SV) determined by various influence parameter which are not analytical acquired
- modifications and further developments shall require little time and effort
- implementing expert knowledge
- manageable in case of imprecise data



Percentage of the AFR repaired components of the three main regions towards the cycles

Functionality:

- directed acyclic graphs
- conditional propability / Bayes‘ theorem: $P(A|B) = \frac{P(B|A)\cdot P(A)}{P(B)}$
- quantitative side: conditional probability tables
- qualitative side: net architecture

[Dreamstime.com]

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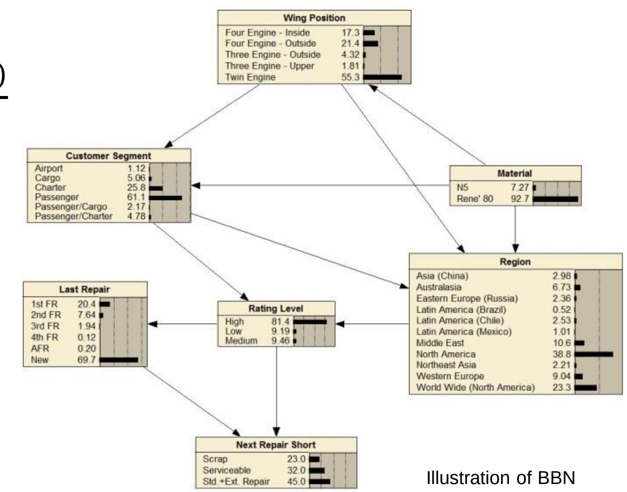


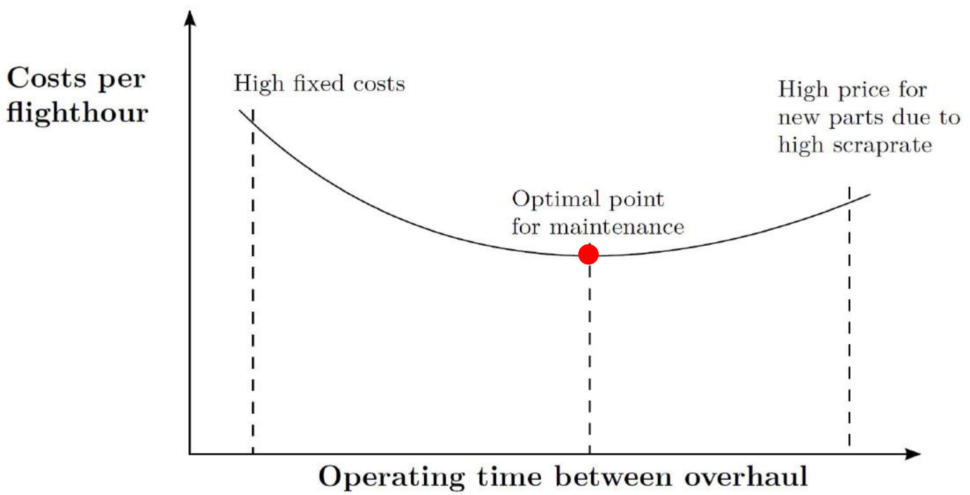
Illustration of BBN

Background

Why using BBN for engine maintenance?

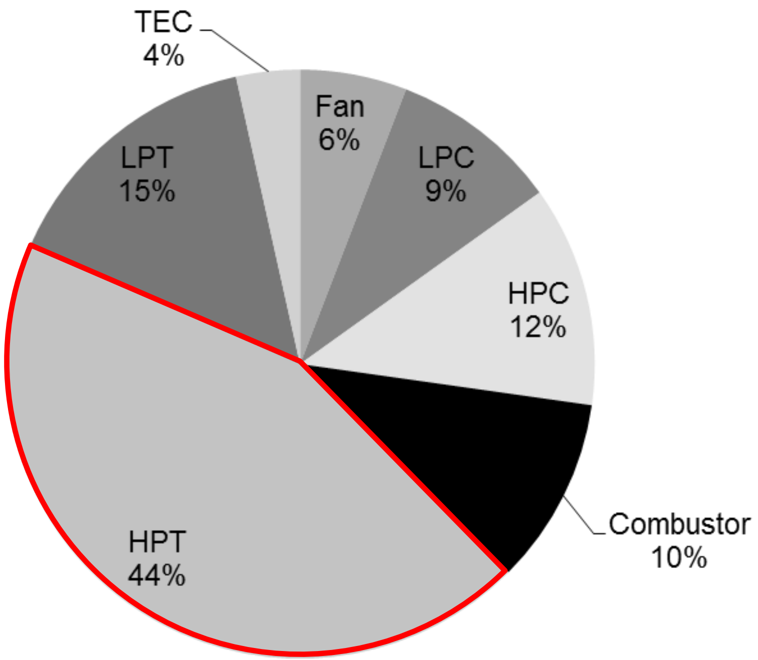
Business side: contractual framework

1. Time and Material
2. Fixed Price
3. Fly by Hour



Optimum time for a shop visit depending on service time and costs, [3]

Main cost driver



Cost driver according to engine modules, modified by [4]

⇒ **precise hardware forecast is badly required**

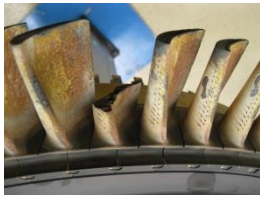
Degradation mechanisms
High-pressure turbine NGVs and rotor blades

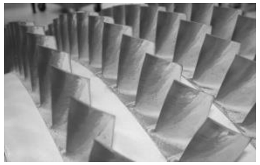
- turbine erosion
- turbine fouling
- hot gas corrosion
- creep & fatigue
- abrasion
- compressor erosion
- compressor fouling
- foreign object damage


Erosion on HPT rotor blades, [5]


Fouling on HPT stator blades, [2]


Hot gas corrosion on HPT blades, [6]


Hot gas corrosion, [7]

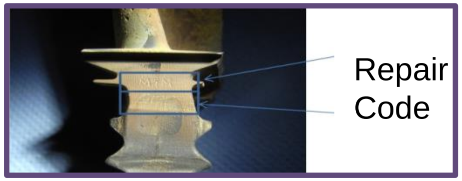

Erosion on HPC rotor blades, [5]


Fouling on HPC blades

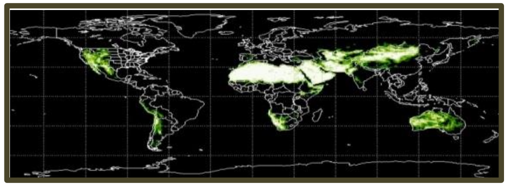

Fan damage

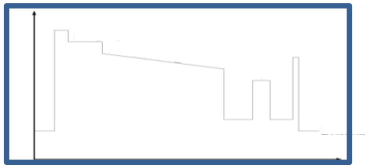
Degradation mechanisms
Input data

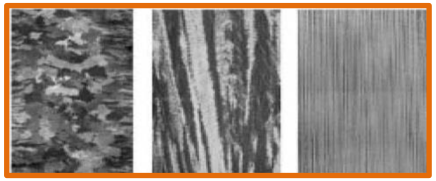
- Last Repair
- Region
- Cycle since last SV
- Material
- Rating Level
- Wing Position
- Aircraft Utilisation



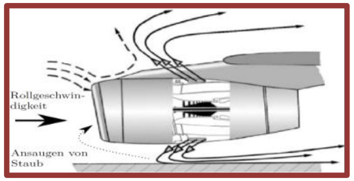
Repair Code Rotor 1.


Dust and sand concentration worldwide [Naval Research Lab]


Flight profile


Blade material [8]

Data entry plug [9]



Reverse thrust operation [9]


Sand ingestion [10]

Aim and objectives

Aim:

- developing a method for forecasting the repair of the HPT NGV
- showing the potential benefit in case of inadequate data density

Objectives/methodology:

Data set
- customer database
- engine manual
- inspection results
- workscopes
- summary of performance

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Net architecture definition
- standard BBN
- quadratic convergence & expert knowledge

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State determination
- Norsys Netica 4.16

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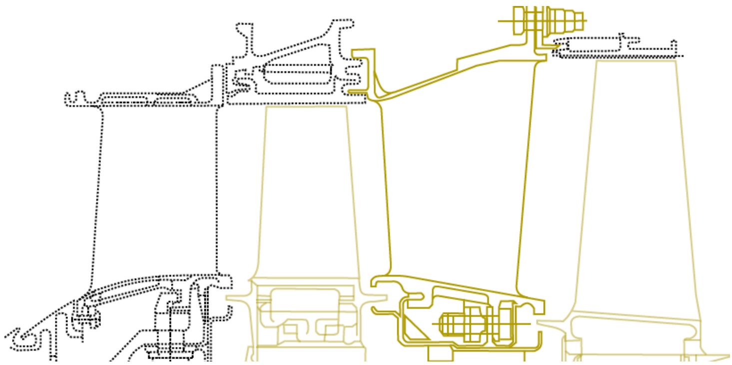
Verification & evaluation
- trend forecasting
- jet engine data se



HPT module, [11]

Framework conditions
Learning data set

Boundary conditions:

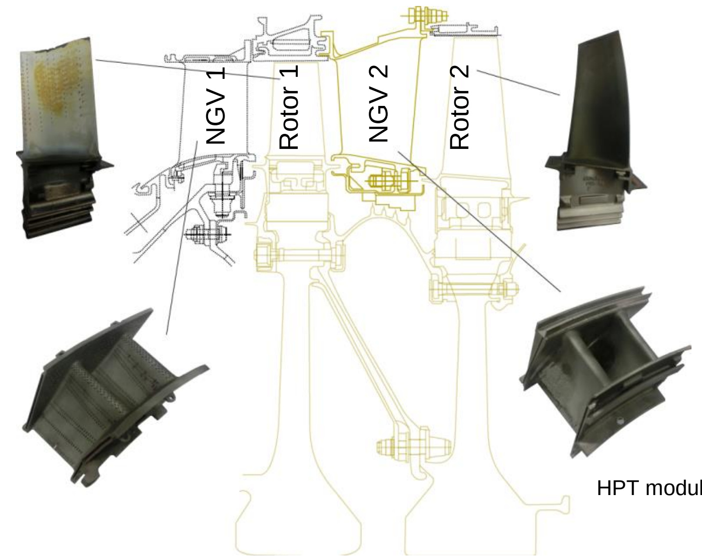
- piece-part repair level
- no unscheduled SV
- engines with recent modification levels
- complete data set

⇒ **~4500 NGV 1** data sets or **~195 jet engines**

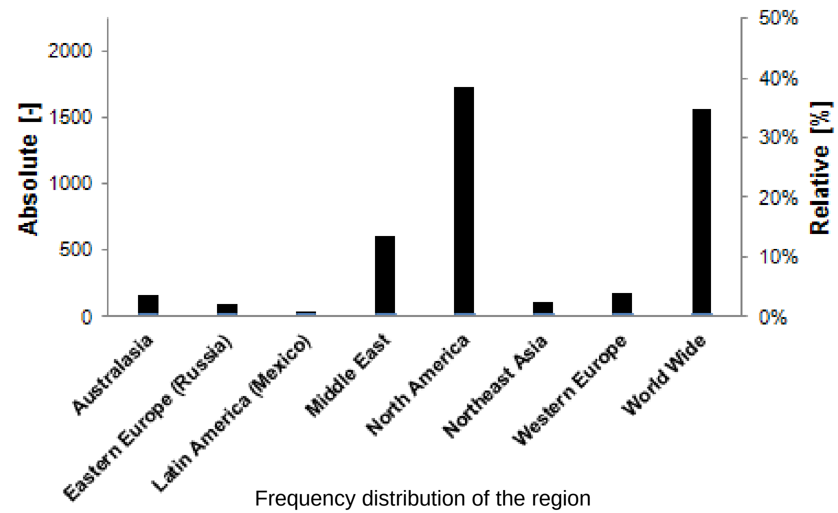
⇒ **~5800 rotor 1** data sets or **~72 jet engines**

⇒ **~8000 NGV 2** data sets or **~333 jet engines**

⇒ **~5600 rotor 2** data sets or **~76 jet engines**



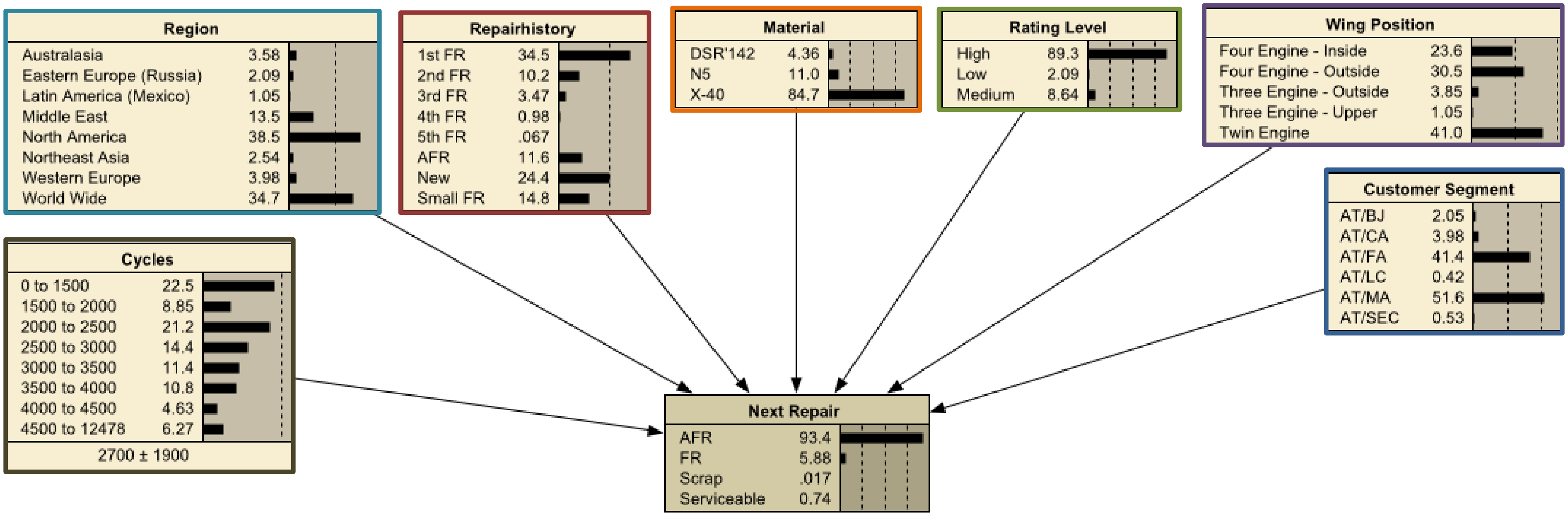
HPT module, [11]



Frequency distribution of the region

Construction of a BBN

Standard BBN (NGV 1)



The standard net

- simplest net architecture
- equal weighting of parameters

Construction of a BBN
Quadratic convergence

Cramer's contingency coefficient:

- detecting correlation for net architecture (qualitative side)

$$C = \sqrt{\frac{\phi^2}{\min\{k-1, m-1\}}}, \qquad 0 \leq C \leq 1$$

ϕ^2: Mean value of quadratic convergence

Maximum value of
k: row
m: column

- Min./max. values:
  1. $C = 0$ → statistical independence
  2. $C = 1$ → ideal statistical dependence
- $C \geq 0.5$: strong correlation between two parameters

Results (NGV 1):

Strong correlation between region and…

- …rating level ($C = 0.84$)
- …customer segment ($C = 0.64$)
- …material ($C = 0.57$)

Strong correlation between material and wing position ($C = 0.48$)

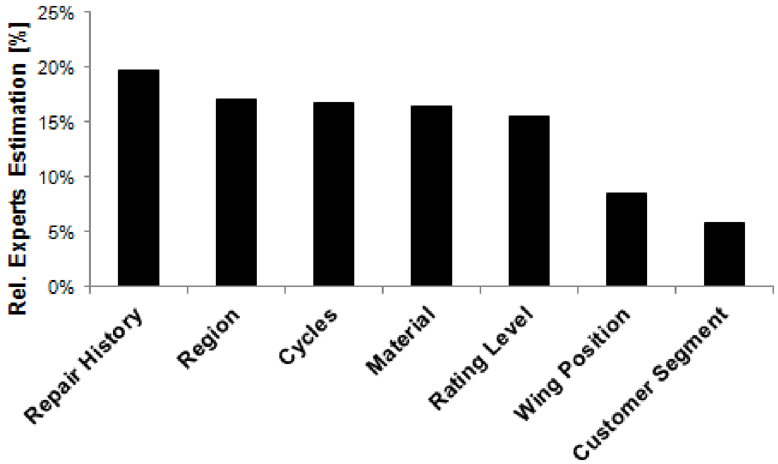
Construction of a BBN
Expert knowledge

Framework:

- in average almost 20 years of experience per person
- up to almost 30 years of experience for one person
- rank the main influences which affect the next repair

Outcome:

- similar order of degradation effects and dominant and environmental conditions
- recent data (years 2011-2014) most suitable
- proposed cycle distribution

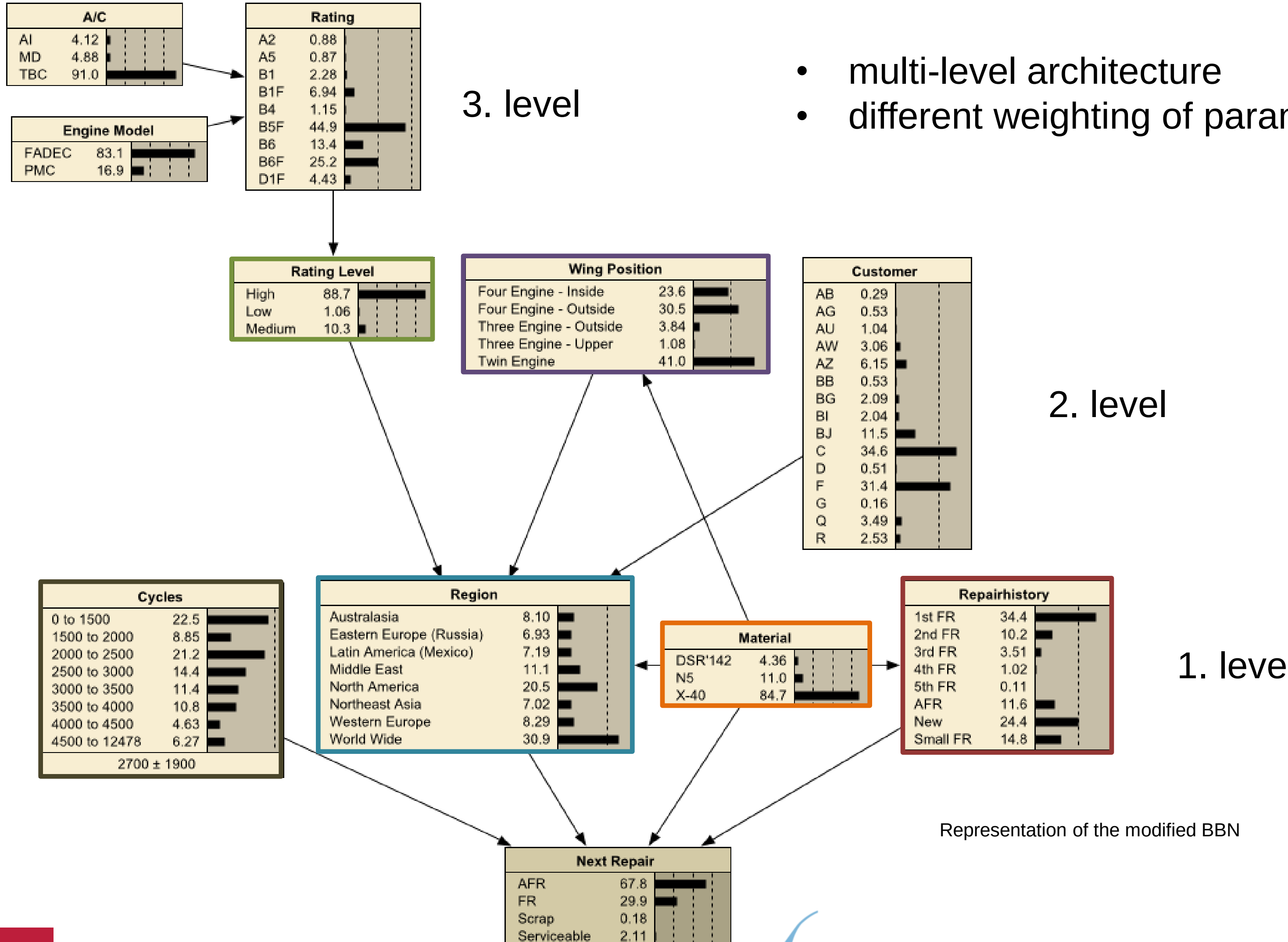


Expert knowledge presentation

Construction of a BBN

Final net architecture – modified BBN (NGV 1)

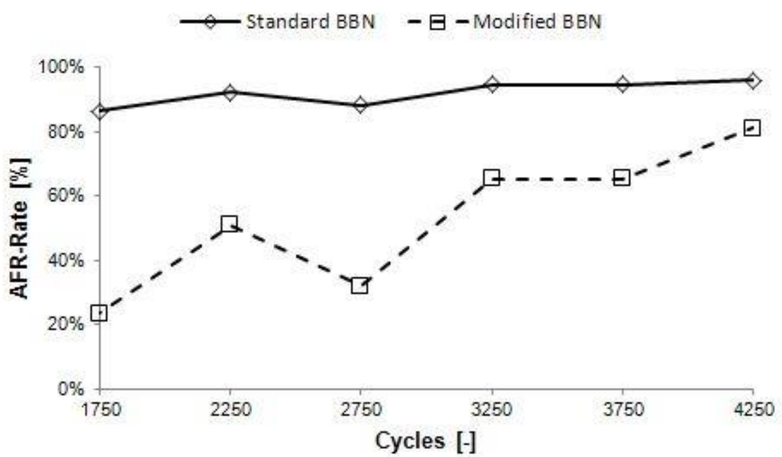
- multi-level architecture
- different weighting of parameters



Representation of the modified BBN

Evaluation – 1
Trend forecasting test cases

- up to eleven test cases generated during expert interview
- specifically for each component
- evaluation by scoring system



Plausibility case five (NGV 1)

Case	Evidences	Expected	Standard net	Modified net
1	2nd FR	~ 100% AFR	✓	✓
2	Middle East, N5, High	~ 100% AFR	✓	✓
3	North America, 2nd FR, X-40	~ 100% AFR	✓	✓
4	Middle East, Cycles ↑	AFR ↑	0	0
5	North America, Cycles ↑	AFR ↑	0	✓
6	Cycles ↑	$AFR_{Outside} > AFR_{Inside}$	X	X
7	Cycles>3000, DSR'142, High	~ 100% AFR	✓	✓
8	North America, Cycles>2500	70% AFR, 30% FR	X	✓
9	High, AT/FA	75% AFR, 25% FR	X	✓
10	New	10% Serviceable	0	0
11	AFR	Serviceable ↓, AFR ↑	0	0

Legend: ✓ good forecast quality
0 medium forecast quality
X poor forecast quality

Trend forecasting test cases (NGV 1)

Evaluation
Results (NGV 1)

Evaluation data set:

- percentage distribution correspond to training data
- limited data used
- **41 test engines:**
    1. 29 **current** engines from August 2012 till January 2013
    2. 2 **unusual** engines
    3. 10 **representative** engines from 2010 till 2012

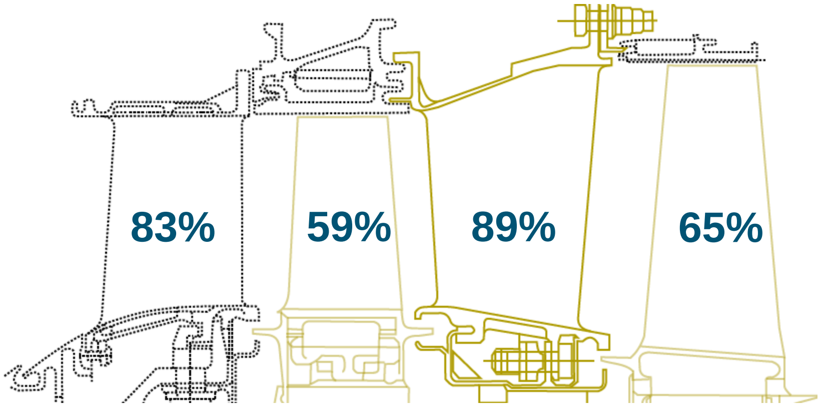
Jet engines	Standard BBN	Modified BBN
All	**77%**	**83%**
Current	80%	85%
Unusual	50%	50%
Representative	73%	85%

List of high accuracy per net

⇒ With up to **83%** the repair of the HPT NGV has been correctly forecasted!

Conclusion

- potential adaptability of the **quadratic convergence test** and **Cramer‘s coefficient** for other hardware components has been shown



HPT module, [11]

- remarks to improve the forecasting quality:
  1. available **data** (less learning data available for rotor blades)
  2. identification of relevant **input parameters**
  3. setting appropriate **boundary conditions**

<u>Outlook:</u>

- very promising potential for contract proposals and capacity planning
  - ⇒ determining the business value
  - ⇒ estimating the statistical variation

- investigating other modules / engine types, also future programmes

Thanks for Listening!

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[Dreamstime.com]

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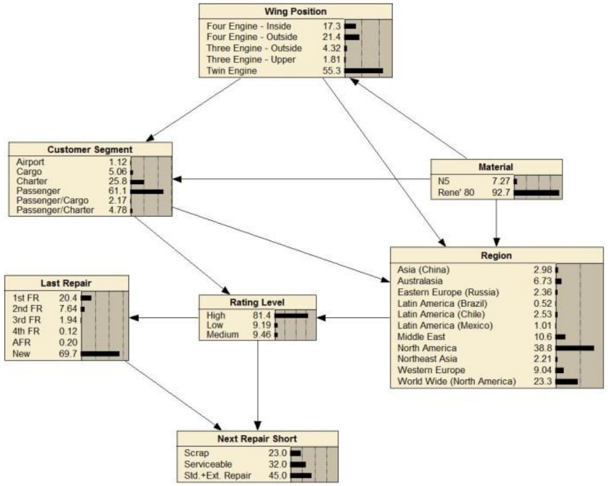

<u>Publications:</u>

[1] Giesecke, D., Friedrichs, J., Kenull, T., Binner, M. and Siegert, M., 2014. "A Method for Forecasting the Condition of HPT NGV's by using Bayesian Belief Networks and a Statistical Approach", GT2014-25464.

[2] Giesecke, D., Wehking, M., Friedrichs, J., Binner, M., "A Method for forecasting the condition of several HPT parts by using Bayesian Belief Networks", GT2015-43110.

Literature

[3] MTU Maintenance Hannover GmbH.

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[7] Meher-Homji, C. B., Chaker, M. A., and Motiwala, H. M., 2001. "Gas turbine performance deterioration". In: Proceedings of the 30th Turbomachinery Symposium.

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[10]Walsh, W. S., Thole, K. A., and Joe, C., 2006. "Effects of sand ingestion on the blockage of film-cooling holes". GT2006-90067).

[11]Friedrichs, J., 2019. "Bauelemente von Strahltriebwerken – Funktion, Betrieb und Wartung", Vorlesungsskript TU Braunschweig.