Modelling of Uncertainties in Reliability Centred Maintenance – a Dempster-Shafer Approach

Uwe Kay Rakowsky, Ulrike Gocht

University of Wuppertal, Germany
University of Applied Sciences Zittau/Görlitz, Germany
Reliability Centred Maintenance

Introduction

Objective

- RCM → find a suitable maintenance strategy
- DS-RCM → express uncertainties of experts in reasoning
- DS-RCM → give weighted recommendations during the RCM process

What’s new?

- Evidence measures belief and plausibility are applied instead of
  → either “yes” or “no” decisions
  → probabilities (ESREL 98)
  → fuzzy membership functions (ESREL 98)

What’s not new?

- RCM process conducted
- RCM diagram applied
- Fundamentals of the Dempster-Shafer Theory (Proceedings)
Reliability Centred Maintenance

Brief Introduction

Detailed Introduction

- IEC 60300-3-11
- Proceedings → references

Five Steps of the RCM Process

- Step ① – Establishing an expert group
- Step ② – Functional breakdown of the system
- Step ③ – Collecting of data
- Step ④ – Tailoring & applying the RCM decision diagram
- Step ⑤ – Documenting results
The RCM Decision Diagram

Brief Introduction

RCM Decision Diagram – Objective

- Find a suitable strategy \(\rightarrow\) component, module, system
- Framework of eight questions, six strategies

![RCM Decision Diagram](image)
The RCM Decision Diagram
Brief Introduction

Note
- Example → mix of *Det Norske Veritas & Marintek*[פעוט]
- Tailor the diagram to your needs!

```
<table>
<thead>
<tr>
<th>Significant consequences</th>
<th>First line maint</th>
<th>no</th>
<th>Detectability of a failure</th>
<th>no</th>
<th>Testability of failure</th>
<th>yes</th>
<th>Periodical tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td></td>
<td>Scheduled maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td></td>
<td>Increasing failure rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td></td>
<td>Find a better design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
<td></td>
<td>yes</td>
<td></td>
<td>Cond based maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes</td>
<td></td>
<td>yes</td>
<td></td>
<td>First line maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>no</td>
<td></td>
<td>Corrective maintenance</td>
</tr>
<tr>
<td>Other reasons for prev maint</td>
<td></td>
<td></td>
<td>First line maint, alone?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Intro
Tailoring a DS Approach
RCM Application
Outro
The Qualitative Approach

Brief Introduction

Drawbacks of Qualitative RCM
- Expert group → consensus required
- “Yes” or “no” → no percentage answer
- Any doubt? → no quantification of doubt
- No weighted recommendations → no ranking of strategies
The Probabilistic Approach

Brief Introduction to $p$-RCM

Introducing Probabilities
- Decision variable $x_i$, $i = 1, \ldots, 8$ (eight questions/decisions)
- “yes” $\rightarrow x_i = 1$, “no” $\rightarrow x_i = 0$
- Expected value $p_i$

Some Interpretations of $p_i$
- Probability that an expert answers “yes” to question $i$
- Degree of an expert’s belief that “yes” is the right decision
- Mean value for decision $i$ resulting from questioning many experts
- Expected value of the binomial distributed decision variable $x_i$

Results $r_i$
- Decision variable $r_i$, $i = 1, \ldots, 6$ (six maintenance strategies)
- Apply the Event Tree method
- $r_1 = (p_1 + q_1 \cdot p_2)(q_3 + p_3 \cdot q_4)q_5p_6$, $\ldots$, $r_6 = q_1 \cdot q_2 \leftarrow DS$-RCM
Tailoring a Dempster-Shafer RCM

Modelling

Scenario
- Frame of discernment
- Hypotheses
- Data sources
- Pieces of evidence

Frame of Discernment
- Only one single question/decision is considered
- Representation → universal set $\Omega$
The Scenario

Modelling

Scenario
- Frame of discernment
- Hypotheses
- Data sources
- Pieces of evidence

Hypotheses
- Single hypothesis → one \textit{answer} to a question
  → “yes”, “no”, or “uncertain”
- Hypotheses → unique \textit{and} not overlapping \textit{and} mutually exclusive
- Universal set \( \Omega \) represents → \( \Omega = \{ \text{“yes”, “no”, “uncertain”} \} \)
- Subsets of \( \Omega \) → single or \textit{conjunctions} of hypotheses
- Set of all subsets → power set \( 2^{\Omega} \)
The Scenario
Modelling

Scenario
- Frame of discernment
- Hypotheses
- Data sources
- Pieces of evidence

Data Sources
- Expert group
  → e.g. service eng., maintenance personnel, system eng., reliability eng.
- Task → give subjective quantifiable statements
- Basis → data, intuition & experience
The Scenario
Modelling

Scenario
- Frame of discernment
- Hypotheses
- Data sources
- Pieces of evidence

Pieces of Evidence
- Piece of evidence $\rightarrow$ expert judgement
- Assignment: piece evidence $\rightarrow$ hypothesis
- Assignment strength $\rightarrow$ quantified by $m$
The Scenario
Modelling

Scenario
- Frame of discernment
- Hypotheses
- Data sources
- Pieces of evidence

Pieces of Evidence
- Piece of evidence $\rightarrow$ expert judgement (data, intuition & experience)
- Assignment
  (evidence $\rightarrow$ hypothesis) corresponds to (cause $\rightarrow$ consequence)
- Assignment
  (1 p-of-e) assigned to (1 hypothesis or 1 set of hypotheses)
  (different p-of-e) may not be assigned to (same hypothesis nor set)
- Quantification
  strength of implication $\rightarrow m(A)$
Sets
- $\Omega$: universal set
- $A \subseteq \Omega$: set, contains a single hypothesis or a set of hypotheses

Basic Assignment
- $m: 2^\Omega \rightarrow [0, 1]$ mapping
- $m(A) = 1$ all statements of an expert are normalised
- $m(\emptyset) = 0$ focal element
- $m(A) = 0$ simplicity (not required)

Differences in Properties to Probabilities
- $m(\Omega) = 1$ not required
- $m(A)$ vs. $m(\neg A)$ no relationship
- If $A \subset B \subseteq \Omega$, then $m(A) \leq m(B)$ not required
Evidential Functions
Dempster-Shafer Calculus

Belief Measure $\text{bel}(A)$
- **Belief** is the degree of evidence that the element in question belongs to the set $A$ as well as to the various special subsets of $A$.
- $\text{bel}(A) = \sum_{B \subseteq A : B \neq \emptyset} m(B)$

Plausibility Measure $\text{pl}(A)$
- **Plausibility** is the degree of evidence that the element in question belongs to the set $A$ or to any of its subsets or to any set that overlaps with $A$.
- $\text{pl}(A) = \sum_{B \cap A \neq \emptyset} m(B)$

![Uncertainty Diagram]

0 1
Belief $\text{bel}(A)$
Plausibility $\text{pl}(A)$

Doubt $1 - \text{bel}(A)$
Disbelief $1 - \text{pl}(A)$
RCM Example

- Condition-based maintenance effective: Do methods exist for effective condition monitoring so that an item failure can be avoided?
- Two answers
- Two experts (example) → two statements
Input & Output

RCM Application

Input
- Statements → “yes”, “no”, or “uncertain”
- Quantification → basic assignments

Cond.-based maintenance effective?
Yes 0.6
No 0.3
Unc 0.1

Yes 0.5
No 0.3
Unc 0.2

No
Input & Output

RCM Application

Input
- Statements → “yes”, “no”, or “uncertain”
- Quantification → basic assignments

Output
- Values of evidential functions
- Certainty → 70% in “yes”
  → 27% in “no”
- Uncertainty → 3%

Cond.-based maintenance effective?
- Yes: bel 0.70, pl 0.73
- No: bel 0.27, pl 0.30
Complements

RCM Application

Complements

- Belief in “yes” versus doubt in “yes” \( \equiv \) plausibility of “no”
- Plausibility of “yes” versus disbelief in “yes” \( \equiv \) belief in “no”

Cond.-based maintenance effective?

Yes
- \( \text{bel} \ 0.70 \)
- \( pl \ 0.73 \)

No
- \( \text{bel} \ 0.27 \)
- \( pl \ 0.30 \)
Weighted Recommendations

RCM Application

Input
- Eight results of every “yes” or “no” decision → values of evidential functions $bel$ and $pl$

Calculus
- Interval arithmetic proceeds (easily)

Output
- Six weighted recommendations on maintenance strategies
- Example, periodical testing $bel = 0.51$, $pl = 0.62$

Significant consequences

First line maint

Detectability of a failure

Testability of failure

Periodical tests

Scheduled maintenance

Find a better design

Cond based maint effective

Cond based maintenance

First line maint, alone?

yes

First line maintenance

Corrective maintenance

Increasing failure rate

no

Other reasons for prev maint

no

Corrective maintenance

Uncertainties in RCM – Dempster-Shafer Approach

Intro

Tailoring a DS Approach

RCM Application

Outro
Conclusion

Outroduction

Comments on the Methods
- Probabilistic, fuzzy-, and Dempster-Shafer RCM → hardly comparable
- \( \text{Prob} \) → one-dimensional value
- \( \text{Fuzzy} \) → graph, peak, results depend on defuzzification method
- \( \text{DS} \) → interval, no peak

Comments on the Results
- Results are close to each other
- Results based on → different interpretations
- Interpretations based on → different theoretical concepts
Conclusion
Outroduction

Even more Comments
- DS calculus → easy to apply → less than one page
- Experts feel more comfortable → degrees instead “yes” or “no”
- Not forced to single strategy → second best?
- etc. →
- DS-RCM offers a different kind of flavour to the maintenance analyst
Modelling of Uncertainties in Reliability Centred Maintenance – a Dempster-Shafer Approach

Uwe Kay Rakowsky, Ulrike Gocht

University of Wuppertal, Germany
University of Applied Sciences Zittau/Görlitz, Germany