Optimal Reliability of Components of Complex Systems Using Hierarchical System Models

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Background

Engineered systems such as:

- electricity/water distribution systems
- structural systems

are complex in the sense that:

- components are functionally/geographically interrelated
- different levels of analyses provided by different experts are required.
Ship hull structure is an example:

- components/(sub-)structures are interrelated:
  - joints
  - plates
  - tanks

- different levels of analyses are required such as:
  - yielding, fracture and corrosion of materials
  - structural analysis
  - consequence analysis.
Objective

To develop a framework for optimization of engineered systems.

- What are effectively designed are components.
- Acceptance criteria are often given for system performance and
- system performance is our direct concern.
**Objective**

The bridge between component and system performance needs to be developed.
The proposed framework relies on the typical characteristics that

- individual components are standardized
- components are hierarchically interrelated

and takes basis in the fact that system performance depends on

- way of interrelation between components
- reliability of components.
Approach

- Modelling of complex systems by Bayesian probabilistic Networks
- Consideration of a-priori given acceptance criteria for system performance
- Setting up an optimization problem
Bayesian probabilistic network:

• is a graphical representation of probabilistic structure of variables by nodes and arrows

• is quantitatively characterized by conditional probability tables

• can provide e.g. expected value, conditional probability

Object-oriented Bayesian probabilistic network:

• is useful when a structure has many identical (sub-) structures/components.
Hierarchical modeling by use of Bayesian probabilistic network

- Component level
Hierarchical modeling by use of Bayesian probabilistic network

- Sub-structure level
Hierarchical modeling by use of Bayesian probabilistic network

- Structure level
On Bayesian probabilistic networks:

expected total cost is written as:

$$u = f(x_1, x_2, ..., x_N)$$

where $x_i$ is design variable for components, e.g. component reliability.

acceptance criteria for system performance are written as:

$$g_j(x_1, x_2, ..., x_N) \leq c_j$$
Optimization of component reliability can be reduced to be a standard constrained optimization problem:

Minimize \[ u = f(x_1, x_2, \ldots, x_N) \]

such that \[ g_j(x_1, x_2, \ldots, x_N) \leq c_j \quad (j = 1, 2, \ldots, M) \]

→ solving the optimization problem with commonly available techniques, e.g. Microsoft Excel and Hugin.
Optimization of reliability of welded joints in ship hull structure

Acceptance criterion: probability of failure of ship hull < 10^{-3}/yr

Objective function: expected total cost
Hierarchical structure of the ship hull:

- Hull structure
- Tanks
- Components

Hull → Ballast tank 1 → Deck plate
- Ballast tank 2
- Cargo tank 1
- Bottom plate
- Side plate
- Tank partition
Corresponding BPN’s:
Conditional probability table

<table>
<thead>
<tr>
<th>CarGoCarGoF</th>
<th>Fail</th>
<th>Survive</th>
<th>Fail</th>
<th>Survive</th>
</tr>
</thead>
<tbody>
<tr>
<td>DecpPlate 1</td>
<td>0.4</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Minor</td>
<td>0.5</td>
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<td>0.19</td>
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<tr>
<td>Major</td>
<td>0.1</td>
<td>0.05</td>
<td>0.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Objective function: $u = f(x_1, x_2, ..., x_{10})$
Constraints: $g(x_1, x_2, \ldots, x_{10}) \leq c$
Excel platform

ActiveX

Solver Add-in

iPlan (Straub and Faber 2006)

Acceptance criteria for system reliability

Minimized expected total cost

Target component reliabilities

Problem Setting

Framework

Example

Conclusion

27.03.2007
• Use of BPN

Engineered system can be hierarchically modelled by use of BPN and especially by object-oriented BPN.

• Standard constrained optimization

  - Objective function: expected total cost
  - Constraints: acceptance criteria for system performance
  - Variables: component reliability

• Use of commonly available techniques/algorithms

  For example, Hugin and Microsoft Excel.