A modelling methodology for the assessment of preventive maintenance on a compressor drive system

European Safety and Reliability (2018 ESREL)  
Trondheim, Norway, 17-21 June

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May 31, 2018
Introduction to the problem

Huge rotary machines are...
- used for separation, compression and boosting
- required to have high reliability

As of today, high cost comes with
- robust-by-design machines
- rigorous preventive maintenance

Therefore,
- move from age- or calendar-based to condition-based maintenance
- assess its benefits and risks

Figure: First compressor train for the Åsgard field (Statoil)
Framework of a typical Compressor Drive System (CDS)

- Multi-unit system
- Degradation and failure
- Condition monitoring
  - Some are continuously monitored
  - Some are periodically inspected
- Maintenance policy
  - Most are under calendar-based maintenance
  - Some are under short-term proactive maintenance
- Seasonal operation profile
  - Full capacity required in peak usage season
  - Reduced capacity in other periods
Problem statement

Questions...

▶ Will the system survive in the coming peak season without loss of production?
▶ How much to gain or lose by changing inspection interval of some components?
▶ Whether to trigger PM out of peak season as we see current system condition?
▶ What to replace during maintenance?
▶ Is it possible to remove unnecessary regular maintenance interventions?

and so on...
System description

Figure: A diagram of six compressor drive trains

Figure: A diagram of one compressor train
VSD and Gear

Figure: Automaton for VSD and Gear

VSD and Gear

Continuously monitored components
Periodically inspected components

Introduction
System description
System modelling
Numerical result
Conclusion

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Compressor

Figure: Automaton for Compressor.
Motor

**Introduction**

*System description*

*System modelling*

*Numerical result*

**Conclusion**

**Continuously monitored components**

**Periodically inspected components**

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**Figure:** Automaton for Motor

\[ \text{outFlow} := \begin{cases} 100 & \text{if } (\text{inflow}=100 \text{ and } \_\text{state}=\text{HIDDEN DEGRADED or REVEALED DEGRADED and OPERATION}) \\ \text{else} & 0 \end{cases} \]
System description

- discrete states with degradation
- perfect monitoring and inspection
- delayed maintenance, time to repair

Figure: One CDS train
Modelling methodology

Figure: Architecture of the model
The modelling language can handle modelling challenges like:

- degradation process, monitoring policies, maintenance rules
- very large state spaces
- information propagation through network of components
- calculation of performance indicators
- reuse of basic patterns
step 1. State-based model for each unit type

Local behaviours

![Automaton for Motor](image-url)

**Figure**: Automaton for Motor.
step 1. State-based model for each unit type

Global commands

**Figure:** Automaton for Motor.
step 1. State-based model for each unit type

Domains and variables

```plaintext
domain State {W, HD, RD, HF, RF}
domain Phase {OP, MAINT, INSP}
domain Season {WINTER, SUMMER}
domain Clock {STB, CALL, READY}
class MOTOR
    State _state (init = WORKING);
    Phase _phase (init = OPERATION);
    Season _season (reset = WINTER);
    Clock _clock (init = STB);
```

Figure: The AltaRica code implementing domains and variables.
step 1. State-based model for each unit type

Events and transitions

transition

degradation: _state==W and _phase==OP -> _state := HD;
failure: _state==HD and _phase==OP -> _state := HF;
failure: _state==RD and _phase==OP -> _state := RF;

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step 1. State-based model for each unit type

Assertion

outFlow := if inflow=100 and (STATE=W or STATE=HD or STATE=RD) and _phase=OP) then 100 else 0;

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step 2. Instance and composition of basic construct

One train

```
class Train
    RepairableUnit VSD;
    RepairableUnit Gear;
    COMPRESSOR Compressor;
    MOTOR Motor;
    Real inflow (reset = 100);
    Real outflow (reset = 100);
    assertion
        VSD.inflow := inflow;
        Motor.inflow := VSD.outflow;
        Gear.inflow := Motor.outflow;
        Compressor.inflow := Gear.outflow;
        outflow := Compressor.outflow;
    ... 
end
```

Figure: AltaRica code implementing one train

Figure: A diagram of one compressor train
step 3. Performance indicators

Figure: A diagram with operational and maintenance profiles
step 3. Performance indicators

```
block Plant
  ...
  Real capacity (reset = 100);
  observer Real Production = production;
  observer Real ProductionLoss = C.demand - production;
  assertion
    ...
    capacity := (T1.outflow + T2.outflow + T3.outflow + T4.outflow +
    T5.outflow + T6.outflow)/6.0;
    production := if C.demand<capacity then C.demand else capacity;
end
```

Figure: The AltaRica code implementing performance indicators
step 4. Model checking

Tools embedded in AltaRicaWizard:
- stepwise simulator
- stochastic simulator

We need to assign in the simulator:
- mission time
- number of simulations
- step etc.
## Input parameters

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<th>VSD</th>
<th>Motor</th>
<th>Gear</th>
<th>Compressor</th>
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</table>
Maintenance optimization scenarios

![Diagram showing maintenance optimization model with branches for inspection interval, failure rate, season profile, time horizon, and maintenance delay.]

Figure: A map of maintenance optimisation scenarios

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Numerical result

Figure: Production and loss versus inspection interval and mission time.
Numerical result

(a) Maintenance delay

(b) Season profile

Figure: Production and loss versus maintenance delay and low demand duration.
Summary

- A preventive maintenance model on a compressor drive system
- Formal modelling formalism AltaRica 3.0
- Multi-unit systems model with constraints
- Health indicators like production and production loss
- Inspection and maintenance assessment and optimisation
Further work

1. degradation profile (exponential, Weibull, empirical distribution)
2. season profile (fluctuations in demand)
3. monitoring policy (inspection effectiveness, scheduling at system level)
4. maintenance policy (intervention priority, system level planning)
Thank you for your attention!

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