Maintenance Optimization with Duration-dependent Costs

A Case Study in Gas Turbine Maintenance Optimization

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Outline

• Industrial gas turbines
• Problem definition
• Model
• Evaluation
• Multi-unit maintenance
• Evaluation
• Conclusions
What is an Industrial Gas Turbine?

Siemens SGT-800, 47 MW. Siemens Press Image
General Electric J85 Jet Engine. Image by Sanjay Acharya, licensed under Creative Commons Attribution ShareAlike 3.0

Siemens SGT5-8000H, 340 MW. Siemens Press Image

Diagram of a typical gas turbine jet engine. Image by Jeff Dahl, licensed under Creative Commons Attribution ShareAlike 3.0
- An US compressor station pumps on average approximately 20 million m$^3$ of natural gas per day.
- Approximately $4$ USD per m$^3$
- Natural gas for $80$ M USD per day!
What is Special About Industrial GTs?

Siemens SGT-600 gas turbine used for mechanical drive in a natural gas compressor station in the Edjeleh gas field in southwest Algeria.

If the unit is down, the pumping capacity of the compressor station is lost or is severely reduced.

*This is true for many gas turbine applications!*

Siemens Press Image
Background

• Maintenance planning software for single turbine
  – Customer: Siemens Industrial Turbomachinery AB
• Deployed early 2008, used mainly for planning after a deviation
• Uses search and heuristics to find solutions
• Global CBM project is in deployment phase
  – PMOpt used in 2 projects
  – Ongoing validation of extended lifetime
• Predicted use is 4-5 operators within 10–15 different operational contracts
• Room for improvement in optimization model
# Application Interface

![Application Interface Diagram]

The diagram above illustrates the application interface for managing components and their periodicity in SICS. The table below shows the components along with their periodicity and consumed lifetime.

<table>
<thead>
<tr>
<th>Component</th>
<th>Periodicity</th>
<th>Consumed Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skovlar</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>Rotor</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Compressor</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Generator</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Cylinder</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Grunka</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Pzyl</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Grej</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Pyttel</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Foobar</td>
<td>11</td>
<td>4</td>
</tr>
</tbody>
</table>

The scenario displayed is 'Test Time periods:', indicating a test scenario for time periods.
# Application Interface

![Screenshot of Application Interface]

<table>
<thead>
<tr>
<th>Optimized</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>PackA_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack1_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack2_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack3_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack4_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack5_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack6_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack7_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack8_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack9_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack10_kin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The screenshot shows a table with columns for different years and rows for various entries. The table appears to be part of a software interface, possibly for project management or task tracking.
Problem Specifics

• Downtime is expensive
  – The production value can be several million USD per day!
  – Manpower is relatively cheap, the main cost driver is the duration of the stops

• The production value varies with time
  – Price of oil and gas

• There can be *opportunities* for low-impact maintenance
  – Other equipment at site must also be maintained
  – Upgrades, etc.

• The predicted lifetime of components change
  – Condition-based Maintenance
Activity Model

• Maintenance items \((i)\) are divided into phases \((p \in 1..P)\) of activities (with phase duration \(\Delta_{pi}\))
  – Phase examples: dismantling, maintenance, testing, refitting, warmup and startup.

• Work in each phase is performed in parallel
• Total work duration:

\[
\sum_{p=1}^{P} \max_{i \in I} \Delta_{pi}
\]

i performed at \(t\)
## Activity Model

<table>
<thead>
<tr>
<th>Shutdown</th>
<th>Cooling and dismantling</th>
<th>Repair</th>
<th>Testing</th>
<th>Startup</th>
</tr>
</thead>
</table>

*Total work duration:*
# Activity Model

<table>
<thead>
<tr>
<th>Shutdown</th>
<th>Cooling and dismantling</th>
<th>Repair</th>
<th>Testing</th>
<th>Startup</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1.1</td>
<td></td>
<td>R1.3</td>
<td>R2.4</td>
<td>R1.5</td>
</tr>
<tr>
<td>R2.1</td>
<td>R2.2</td>
<td>R3.3</td>
<td>R3.4</td>
<td>R2.5</td>
</tr>
<tr>
<td>R3.1</td>
<td>R3.2</td>
<td>R4.3</td>
<td>R4.4</td>
<td>R3.5</td>
</tr>
<tr>
<td>R4.1</td>
<td>R4.2</td>
<td>R5.3</td>
<td></td>
<td>R4.5</td>
</tr>
<tr>
<td>R5.1</td>
<td>R5.2</td>
<td></td>
<td></td>
<td>R5.5</td>
</tr>
</tbody>
</table>

Total work duration:
Activity Model

Total work duration:
Activity Model

Total work duration:

R2.1  R4.2  R1.3  R3.4  R1.5
Downtime Model

• Each maintenance stop can take days or even weeks

• We must include resting time:
  – Each day, a shift works $A$ hours (usually 10 hours)
  – Sunday’s are off

• Total downtime ($w_t$ is working time at $t$):

$$v_t = w_t + \max \left( 0, (24 - A) \left[ \frac{w_t}{A} - 1 \right] + 24 \left[ \frac{w_t}{6A} - 1 \right] \right)$$
## Downtime Model

<table>
<thead>
<tr>
<th>Shutdown</th>
<th>Cooling and dismantling</th>
<th>Repair</th>
<th>Testing</th>
<th>Startup</th>
</tr>
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<tr>
<td>R1.1</td>
<td></td>
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<td>R2.4</td>
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<tr>
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<td></td>
<td>R2.5</td>
<td></td>
</tr>
<tr>
<td>R3.1</td>
<td>R3.2</td>
<td>R3.3</td>
<td>R3.4</td>
<td></td>
</tr>
<tr>
<td>R4.1</td>
<td>R4.2</td>
<td>R4.3</td>
<td>R4.4</td>
<td></td>
</tr>
<tr>
<td>R5.1</td>
<td>R5.2</td>
<td>R5.3</td>
<td>R4.5</td>
<td></td>
</tr>
</tbody>
</table>

*Total work duration:*

<table>
<thead>
<tr>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night</td>
<td>Night</td>
<td>Night</td>
<td>Night</td>
<td>Night</td>
<td>Rest</td>
<td>Night</td>
<td>Night</td>
</tr>
</tbody>
</table>
Downtime Model

Total work duration:

Tuesday  Wednesday  Thursday  Friday  Saturday  Sunday  Monday  Tuesday
R2.1     Night     R4.2     Night     Night     Night     R3.4     Night  Rest  Night  Night
Objective

\[
\min_{x,y,v,w,r^N,r^W} f = \sum_{i=1}^{I} \sum_{t=1}^{H} C_i x_{it} + \sum_{t=1}^{H} S_t y_t + \sum_{t=1}^{H} D_t v_t
\]

- **Maintenance Costs**
- **Setup Costs**
- **Production Loss**

\[+ \varepsilon \sum_{i \in I} \sum_{t=1}^{H} (H - t) x_{it}\]

- **Earliness**
Model (1)

\[
\begin{align*}
&\sum_{j=t}^{t+T_i} (x_{ij} + \sum_{i' \in N_i} x_{i'j}) \geq 1 \\
&\sum_{j=1}^{T_i-O_i} (x_{ij} + \sum_{i' \in N_i} x_{i'j}) \geq 1 \\
x_{it} \leq y_t \\
\Delta_{pi} x_{it} \leq w_{pt} \\
r_t^N \geq \frac{\sum_{p=1}^{P} w_{pt}}{A} - 1 \\
r_t^W \geq \frac{\sum_{p=1}^{P} w_{pt}}{WA} - 1 \\
\end{align*}
\]

\(\forall i \in I, t \in 1..H - T_i\)  \hspace{1cm} (2)

\(\forall i \in I\) where \(T_i - O_i \leq H\)  \hspace{1cm} (3)

\(\forall i \in I, t \in 1..H\)  \hspace{1cm} (4)

\(\forall i \in I, p \in 1..P, t \in 1..H\)  \hspace{1cm} (5)

\(\forall t \in 1..H\)  \hspace{1cm} (6)

\(\forall t \in 1..H\)  \hspace{1cm} (7)
Model (2)

\[ v_t = \sum_{p=1}^{P} w_{pt} + (24 - A)r_t^N + 24r_t^W \quad \forall t \in 1..H \]  

\[ v_t \leq k_{pt} \quad \forall t \in 1..H \]  

\[ \sum_{t=1}^{H} v_t \leq (24 \cdot 7 \cdot H)(1.0 - \alpha) \]  

\[ r_t^N, r_t^W \geq 0, \text{ integer} \quad \forall t \in 1..H \]  

\[ x_{it}, y_h \text{ binary} \quad \forall i \in I, t \in 1..H \]
Experimental Setup

- 15-year contract, week level
- Standard and extended-life schedules
- Movement of up to 12 weeks from deadline possible
- Mean result of 10 runs

- **Fix**: Downtime fixed at 100 per hour
- **Var**: Downtime cost from $N(100,50)$ per hour
- **Opp**: 10% zero-cost opportunities
- **Sync**: Equal wear for all components
- **Rnd**: Random wear from uniform distribution
- **Block**: Perform maintenance at deadline
- **Opt**: Optimized maintenance
Varying Allowed Activity Mvmt.

Standard Life Varying Prod. Value 10% Opportunities

Allowed Movement (weeks)
Varying Duration Limit

Capacity = Factor of maximum item duration

Standard Life Varying Prod. Value 10% Opportunities Max 12w. mvmt.
Activity Inclusion

• Common that activities include each other:
  – A major overhaul includes all work in a minor overhaul
  – A minor overhaul includes an oil change
  – An oil change includes a visual inspection
  – A visual inspection includes nothing

• What effect does this have?
Effect of Dependencies

Varying Prod. Value
10% Opportunities
Infinite Movmt.
Redundant Gas Turbines

• The system consists of $n$ turbines
• Out of these, $k$ turbines have to work
  – Otherwise some production capacity is lost
  – Common in oil and gas applications
• High availability due to redundancy
• Redundant turbines in cold standby
Multi-Unit Model, $k$-out-of-$n$

$$\min_{x,y,z,w,v} f = \sum_{u=1}^{k} \sum_{i=1}^{I} \sum_{t=1}^{H} C_i x_{uit} + \sum_{t=1}^{H} S_t y_t + \frac{28}{A} \sum_{t=1}^{H} D_t v_t$$

- **Maintenance Costs**
- **Setup Costs**
- **Production Loss**

$$+ \varepsilon \sum_{u=1}^{k} \sum_{i \in I} \sum_{t=1}^{H} (H - t) x_{uit}$$

- **Earliness**
Multi-Unit Model (2)

\[
\begin{align*}
\sum_{j=t}^{i+T_i} (x_{uij} + \sum_{i' \in N_i} x_{ui'j}) & \geq 1 & \forall u, i, t \in 1..H - T_i \\
\sum_{j=1}^{T_i - O_{ui}} (x_{uij} + \sum_{i' \in N_i} x_{ui'j}) & \geq 1 & \forall u, i \text{ where } T_i - O_{ui} \leq H
\end{align*}
\] (8) (9)

\[
x_{uit} \leq y_t & & \forall u, i, t
\] (10)

\[
\sum_u z_{ut} = n - k & & \forall t
\] (11)

\[
\Delta_{pi}(x_{uit} - z_{ut}) \leq w_{upt} & & \forall u, i, p, t
\] (12)

\[
\sum_{p=1}^{P} w_{upt} \leq v_t & & \forall u, t
\] (13)

\[
w_{upt}, v_t \geq 0 & & \forall u, p, t
\] (14)

\[
x_{uit}, y_t, z_{ut} \text{ binary} & & \forall u, i, t
\] (15)
Experimental Setup

• 2-out-of-3 system
• Maintenance of 1 turbine doesn’t cause downtime
• Plan for 3.25 years
• Max 12 week movement of items
Maintenance Cost, Std. life

- var
- var-opp
- fix
- fix-opp

Sync-Block
Sync-Opt
Rnd-Block
Rnd-Opt

Maintenance Cost, Std. life

M. Bohlin
Maintenance Cost, Ext. life
Effects of Single Failure

![Graph showing maintenance cost against failure of component number with two lines representing Block Repair and Optimization.]
Summary

• Maintenance scheduling with downtime-dependent costs
  – NP-complete, MIP model based on the Chalmers model

• Single gas turbine
  – Actual availability increase 0.5-1.0%
  – Cost savings in the order of million dollars per year
  – Capacity limits had little impact, inclusion dependencies larger impact

• Multiple gas turbines
  – Significant effects on maintenance costs
  – Small effects on downtime due to redundancy
  – Significant effects at disturbances (breakdowns)

• Future work:
  – Corrective maintenance and risk levels
  – Multi-unit Train Maintenance
Thank you for your attention!