Optimization of maintenance planning at Volvo Aero Corporation (VAC)

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Industrial Mathematics

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2 October 2007

Background

Maintenance of aircraft engines is expensive:

- *spare parts* cost up to 2 Mkr
- *total cost* for maintenance of a jet engine: 15-30 Mkr
- *rent* for a spare engine: 15 kkr/day

Opportunistic maintenance:

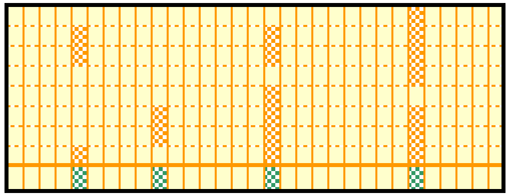
At each maintenance occation, possible to *replace more componentes than* what is absolutely *necessary*

⇨ totally fewer maintenance occations

⇨ totally lower cost

The purpose of the project

- Create a *methodology* that generates good *replacement schedules* for components in aircraft engines



- Consider:
  - *Life time restricted* and *”on condition”*-components
  - *Fixed cost* when an engine/module is taken to the workshop
  - *Work costs* to set free engine modules and components
  - Utilize a *store* of used components
- *Minimize total flight hour cost* during the contract period

An optimization model for the whole contract period

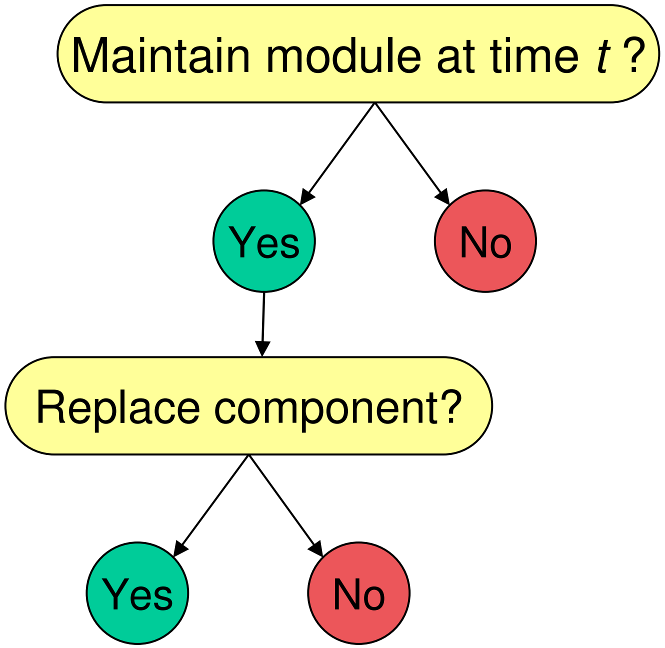
- For each component i in the module:
  - *Cost* for a new component: c_i
  - *Life* of a new component: T_i
  - *Remaining life* of current component: τ_i
- *Contract period* divided into T *time periods* $t = 1,\ldots,T$ (a' 50 flight hours)
- Maintenance possible at start of each time period (*discrete time steps*)
- A *fixed cost* per maintenance occation: d

A mathematical optimization model for maintenance planning of a module

Definition of variables

$$z_t = \begin{cases} 1 & \text{if the module is maintained at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$x_{it} = \begin{cases} 1 & \text{if component } i \text{ is replaced at time } t \\ 0 & \text{otherwise} \end{cases}$$



Basic mathematical model: one module, *N* parts, *T* time steps

minimize $\displaystyle\sum_{t=0}^{T-1}\left(\sum_{i\in N} c_i x_{it} + d z_t\right)$

subject to

$$\sum_{t=0}^{\tau_i} x_{it} \geq 1, \qquad i \in N,$$ replace part before its remaining life is over

$$\sum_{t=l}^{T_i+l-1} x_{it} \geq 1, \qquad l = 1,\ldots,T-T_i, \quad i \in N,$$ replace part at least once in a lifetime

$$x_{it} \leq z_t, \qquad t = 0,\ldots,T-1, \quad i \in N,$$ replace part only at maintenance occation

$$x_{it} \in \{0,1\}, \qquad t = 0,\ldots,T-1, \quad i \in N,$$

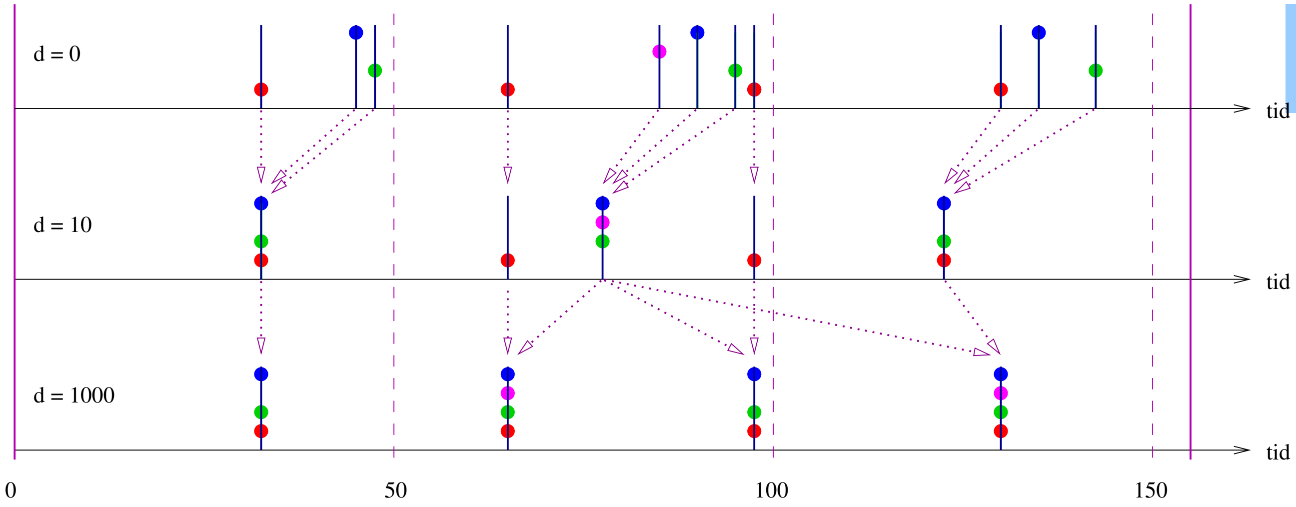
$$z_t \in \{0,1\}, \qquad t = 0,\ldots,T-1.$$

- $x_{it} \in \{0,1\}$ can be relaxed to $x_{it} \geq 0$ — Integrality property (TU)!

Costs for spare parts vs. fixed maintenance costs

d = fixed cost per maintenance occation (inspection, transport, admin, ...)

Optimal maintenance plans for 3 levels of the fixed cost



Replace only broken parts
⇨many maintenance occations

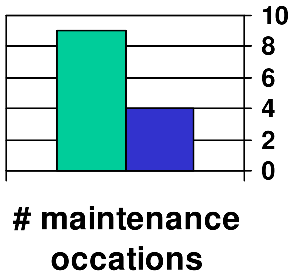
Accumulated maintenance at fewer occations

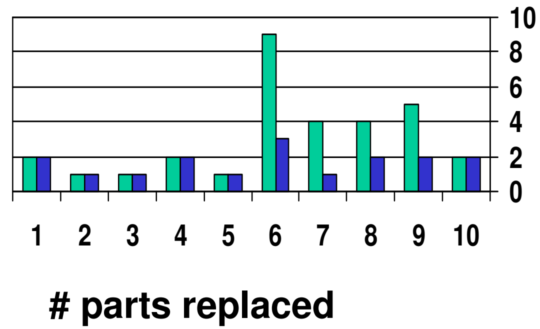
More replacements, even fewer occations

Comparison of the methods

- An engine module with 10 components
- Only life time restricted components

- Value policy
- Optimization



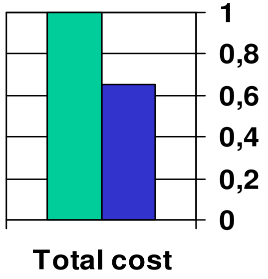


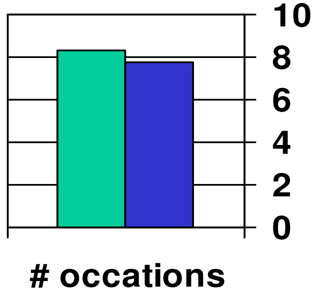
Comparison of the methods using stochastic simulations

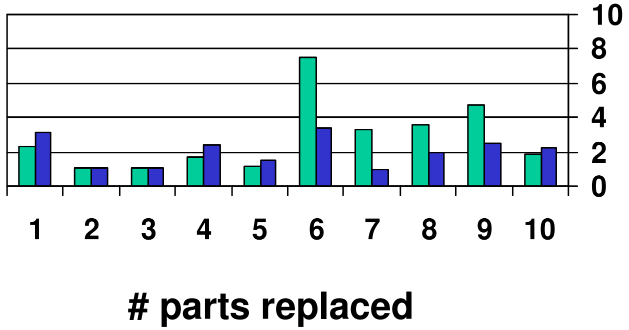
- An engine module with 10 components
- Parts 1, 4, 5, 6, 9, 10 are OC (Weibull)

Part no	1	4	5	6	9	10
β	2	2	4	4	6	6

- Average values from 200 scenarios







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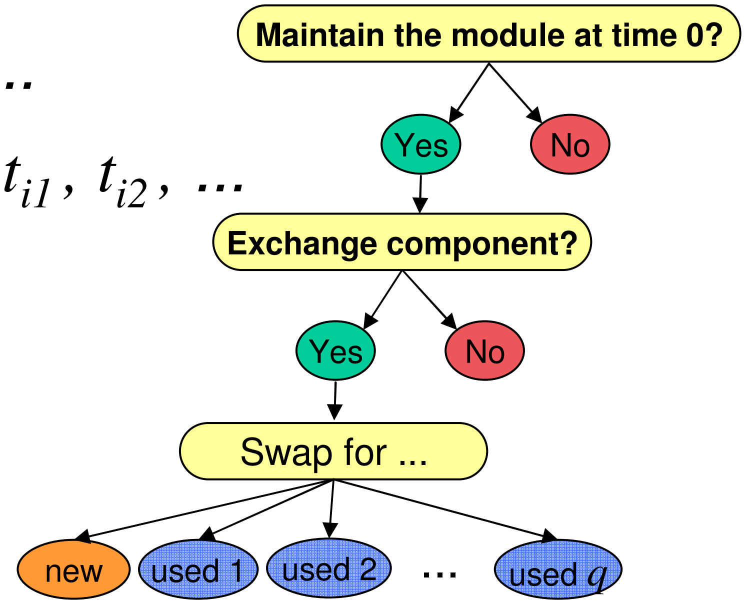
Conclusions from the simulations

- Optimization ⇨ *always best plan w.r.t. cost (10-30% savings)*
- Solution time typically a few CPU-seconds (one module)
- Compared also with
  - *”age policy”* (replace part older than a certain age limit, optimize age limits)
  - *”no method”* (replace only broken parts, not opportunistic)
  - The optimization model is *best* also here
- Optimization ⇨ *fewer maintenance occations*

A store of used components

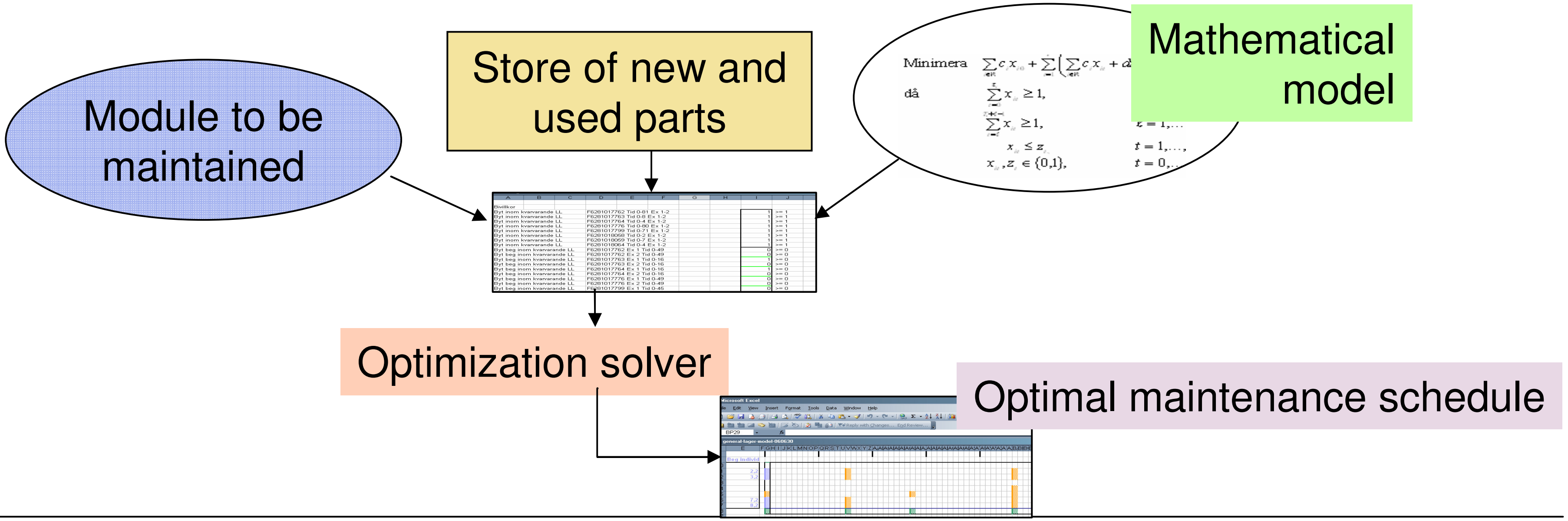
- For each part i in the module there is a *store of used components* at time 0 (at present maintenance occation):
  - *Costs* for used components: $k_{i1,}\ k_{i2}\ ,\ \ldots$
  - *Remaining lives* of used components: $t_{i1}\ ,\ t_{i2}\ ,\ \ldots$
- Additional variables:

$$s_{ij} = \begin{cases} 1 & \text{if used individual } j \text{ of component } i \\ & \text{from the store is used at time } 0 \\ 0 & \text{otherwise} \end{cases}$$



A tool for optimization and decision support at maintenance planning

- For one engine module and a store of new and used (at time 0) parts
- *Implemented in Excel* for input and presentation of results
- With Xpress-MP as IP solver



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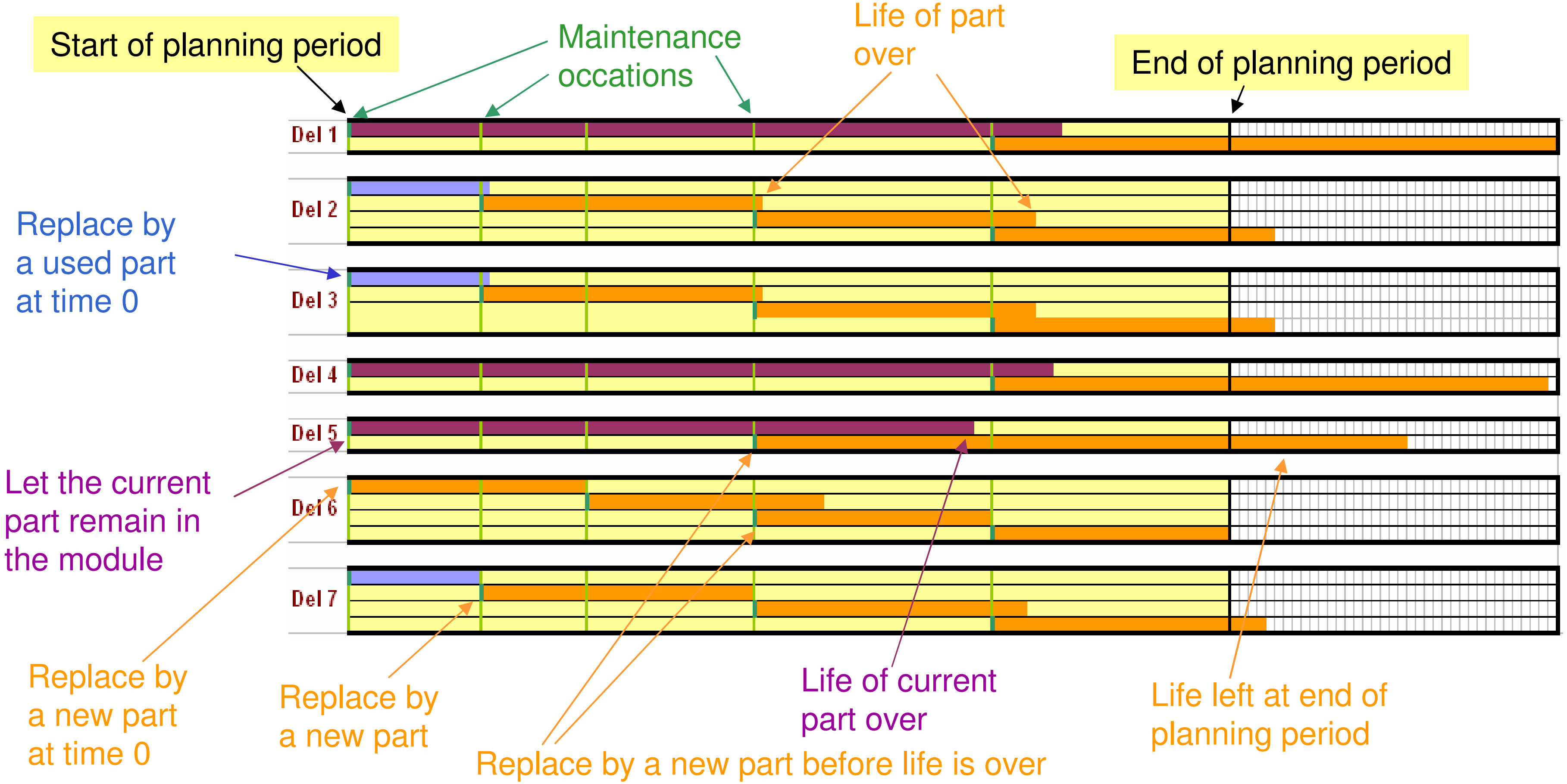
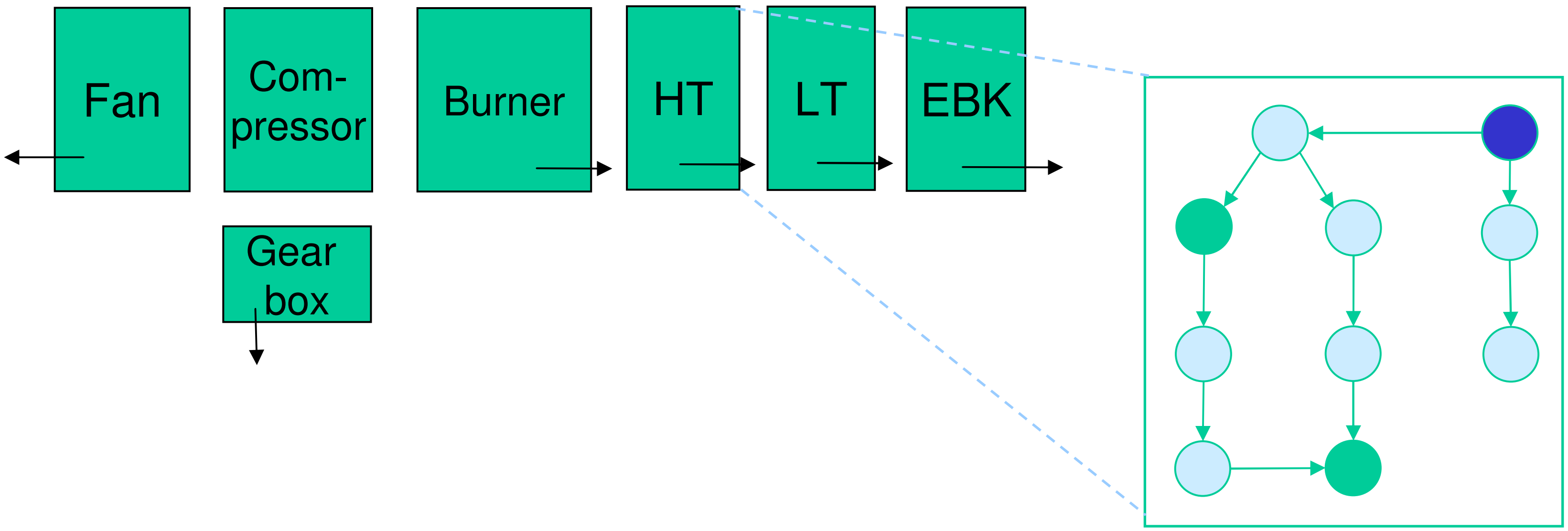
An optimal maintenance schedule for 7 components in an engine module



Several modules in an engine

- *Work costs* to *set modules free*
- *Work costs* to *set components* free



A model for a whole engine

Variable definition

$$x_{it}^{m} = \begin{cases} 1 & \textit{if} \text{ component } i \text{ in module } m \text{ is replaced at time } t \\ 0 & \textit{otherwise} \end{cases}$$

$$y_{it}^{m} = \begin{cases} 1 & \textit{if} \text{ component } i \text{ in module } m \text{ is removed at time } t \\ 0 & \textit{otherwise} \end{cases}$$

$$w_{t} = \begin{cases} 1 & \textit{if} \text{ the engine is maintained at time } t \\ 0 & \textit{otherwise} \end{cases}$$

$$v_{nt} = \begin{cases} 1 & \textit{if} \text{ acitivity } n \text{ is done at time } t \\ 0 & \textit{otherwise} \end{cases}$$

$$z_{t}^{m} = \begin{cases} 1 & \textit{if} \text{ module } m \text{ is maintained at time } t \\ 0 & \textit{otherwise} \end{cases}$$

A model for a whole engine

Includes:

- *Costs* for several *work tasks*
- *Dependencies* between components – graph structure
- Possibility to *fix* certain *activities* in advance

$$\text{minimize} \quad \sum_t \left(\sum_m \left(\sum_i \left(c_i^m \cdot x_{it}^m + a_i^m \cdot y_{it}^m \right) \right) + d_t \cdot w_t + \sum_n b_n \cdot v_{nt} \right)$$

$$\text{subject to} \quad \sum_t z_t^m \le T f_m \qquad \forall M$$

$$\sum_{t=0}^{\tilde{T}_i^m} x_{it}^m \ge f_m \qquad \text{if } (\tilde{T}_i^m \le T-1),\ i \in N^m,\ \forall m$$

$$\sum_{t=l}^{T_i^m + l - 1} x_{it}^m \ge f_m \qquad l = 1, \ldots, T - T_i^m,\ i \in N^m,\ \forall m$$

$$\sum_{j \in \delta^m(i)} y_{jt}^m \ge y_{it}^m \qquad i \in N^m,\ \forall m,\ \forall t$$

$$z_t^m \le \sum_{n \in A^m} v_{nt} \qquad \forall m,\ \forall t$$

$$v_{nt} \le \sum_{n' \in A(n)} v_{n't} \qquad \forall n,\ \forall t$$

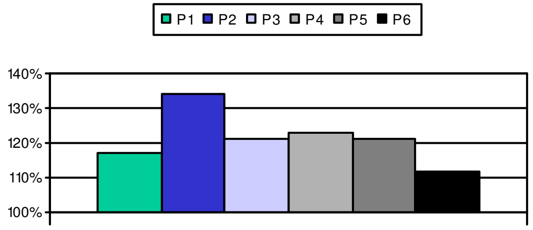
$$x_{it}^m \le y_{it}^m \le z_t^m \le w_t \qquad i \in N^m,\ \forall m,\ \forall t$$

$$y_{it}^m,\ z_t^m,\ v_{nt} \in \{0,1\} \qquad i \in N^m,\ \forall m,\ \forall n,\ \forall t$$

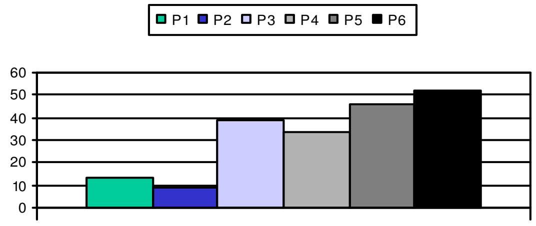
$$x_{it}^m,\ w_t \ge 0 \qquad i \in N^m,\ \forall m,\ \forall t$$

Results from initial tests for a whole engine

First maintenance plan



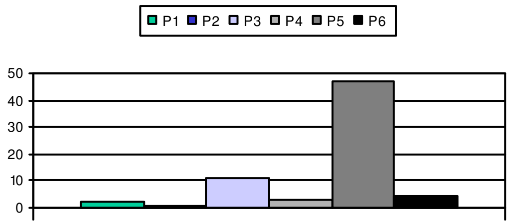
100% = optimal value



CPU seconds

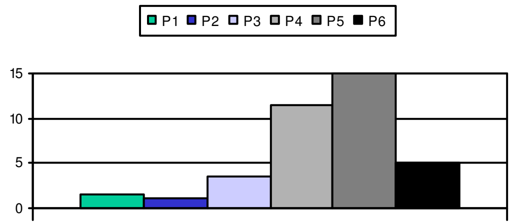
P1–P6: six models with different levels of inclusion of work costs

≤ optimal value + 10%



CPU minutes

≤ optimal value + 5%



CPU hours

Model for a whole engine – several magnitudes harder than for one module

More ...

- Alternative *solution approaches*, decomposition methods:
- Solve the basic model very many times
  - Benefit from solving it efficiently
- Study the *structure* of the basic mathematical *model*
  - New formulations ⇨ significant *reduction of execution time*
- Tests are going on
  - Vary fixed costs and # time steps
  - Vary age of existing engine
  - How good is the first feasible solution found (for time 0)?