Optimization of maintenance plans for aircraft engines—application to operations at Volvo Aero

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Opportunistic maintenance

- Maintenance work and spare parts are often costly
- Available resources must be efficiently utilized

⇒ **Each maintenance occasion is an opportunity to do preventive maintenance**

- We develop quantitative models and methods with the goal to find optimal maintenance plans

Joint work with

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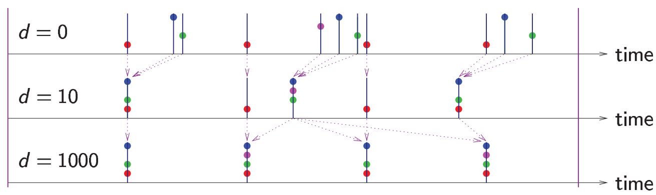
- Dr Torgny Almgren, Volvo Aero Corporation
- Prof Michael Patriksson, Chalmers MV
- Dr Myrna Palmgren, Chalmers MV

Opportunistic maintenance planning may yield large profits from coordination

- A system with four components, with different lives and costs
- d: maintenance occasion cost (normalized)

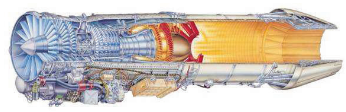


Principles for maintenance

- **Preventive maintenance:** replace/repair before a failure occurs
- **Corrective maintenance:** replace/repair after a failure has occurred
- **Condition based maintenance:** measure prior to the decision on maintenance
- **Reliability based maintenance:** focus on the functioning of the system at each point in time
- **Opportunistic maintenance:** utilize necessary (e.g. corrective) maintenance occasions to do preventive (and condition/reliability based) maintenance

A research project in cooperation with Volvo Aero

- Aircraft engines are costly to maintain:
  - Spare parts: ≤ 2 MSEK
  - Rent a spare engine: 15 kSEK/day
  - Maintenance duration: 1–3 months



- Project goal: Minimize total flight hour cost during the contract period
- Means: Create a methodology that generates good replacement schedules for components
- Component have limited lives or are on condition
- Fixed cost to take an engine/module to the maint. workshop
- Work costs to (dis)assemble modules/components

An optimization model for an engine module over a contract period

- For each component i in the module:
  - Cost of a new component: c_i
  - Life of a new component: T_i
  - Remaining life of the component individual currently in the module: τ_i
- The contract period is divided into time steps $t = 1, \dots, T$
- Maintenance can be done at the beginning of each time step
- A fixed cost per maintenance occasion: d

The replacement problem for one engine module

- Minimize the total cost of a functioning module during the contract period
- Variables:

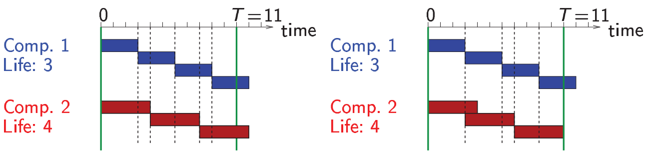
$$x_{it} = \begin{cases} 1, & \text{if component } i \text{ is replaced at time } t \\ 0, & \text{otherwise} \end{cases}$$

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

$$\text{minimize} \quad \sum_{t=1}^{T} \left(\sum_{i=1}^{N} c_{it} x_{it} + d_t z_t \right),$$

$$\begin{aligned} \text{subject to} \quad \sum_{t=\ell+1}^{\ell+T_i} x_{it} &\geq 1, & \ell &= 0, \dots, T-T_i, & i &= 1, \dots, N \\ x_{it} &\leq z_t, & t &= 1, \dots, T, & i &= 1, \dots, N \\ x_{it}, z_t &\in \{0,1\}, & t &= 1, \dots, T, & i &= 1, \dots, N \end{aligned}$$

A simple illustration of an optimal replacement schedule



- The system must function between the times 0 and $T = 11$
- Five replacements, cost: $3c_1 + 2c_2 + 5d$
- Minimum cost for maintenance: $3c_1 + 2c_2 + 4d$

Constraint structure—example

- Component 3: $\sum_{t=\ell+1}^{\ell+T_3} x_{3t} \geq 1,\ \ell = 0, \dots, T - T_3$
- $T = 8,\ T_3 = 4 \quad \Longrightarrow \quad \sum_{t=\ell+1}^{\ell+4} x_{3t} \geq 1,\ \ell = 0, \dots, 4$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_{31} \\ x_{32} \\ \vdots \\ x_{38} \end{bmatrix} \geq \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

- A special type of set covering constraints that possess unimodularity:

$\Rightarrow$ The constraints $x_{it} \in \{0,1\}$ may be relaxed to $x_{it} \in [0,1]$

- Optimal solutions will be integer anyway

Mathematical modelling

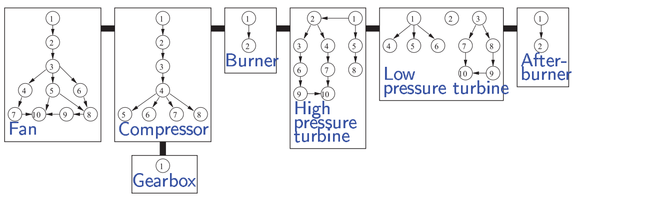
- Our variables are logical: *do something or not*
  - Modelled with *binary variables*:

$$x_t = \begin{cases} 1, & \text{if something is done at time } t \\ 0, & \text{otherwise} \end{cases}$$

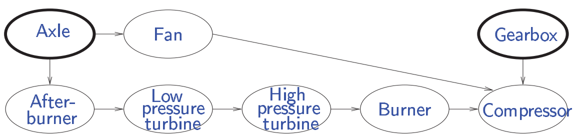
- A decision on a certain measure often force other measures to be taken:
  - E.g., to replace component i maintenance must be performed
- These logical relations can be expressed by *linear constraints*:

$$\text{if A then B} \quad \Longleftrightarrow \quad x_A \leq x_B$$

The modular structure of the engine



Disassembly activity network for the engine modules

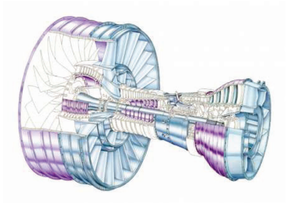


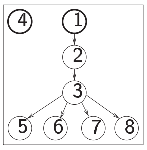
The gearbox **and** the fan **and** the burner must be removed **before** the compressor can be removed

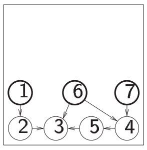
Connections between components in modules: interdependency networks

- Component 8 (left) is reached by: $1 \to 2 \to 3 \to 8$
- Component 3 (right) is reached by: $1 \to 2 \to 3$ or $6 \to 3$ or $6 \to 4 \to 5 \to 3$, or $7 \to 4 \to 5 \to 3$

$\Rightarrow$ Very many combinations of component replacements, each time step







A mathematical optimization model for the whole engine, I

- Goal: minimize costs

$$\sum_{t=1}^{T}\left(\sum_{m\in\mathcal{M}}\left[\sum_{i\in\mathcal{N}^m}(c_{it}^m x_{it}^m + a_{it}^m y_{it}^m)\right] + d_t w_t + \sum_{n\in\mathcal{A}} b_{nt} v_{nt}\right)$$

- All decision variables are binary

$$x_{it}^m, y_{it}^m, z_t^m, v_{nt}, w_t \in \{0,1\},\ t=1,\dots,T,\ i\in\mathcal{N}^m,\ m\in\mathcal{M},\ n\in\mathcal{A}$$

- Replace each component before its life is over

$$\sum_{t=1}^{\overline{T}_i^m} x_{it}^m \ge 1 \quad i\in\mathcal{N}^m : \overline{T}_i^m \le T, \quad m\in\mathcal{M}$$

$$\sum_{t=\ell+1}^{\ell+T_i^m} x_{it}^m \ge 1 \quad \ell=0,\dots,T-T_i^m, \quad i\in\mathcal{N}^m : T_i^m \le T,\ m\in\mathcal{M}$$

Costs associated with maintenance activities

- Transportation costs
- Administration costs
- Indirect costs to replace the missing engine (lease cost or costs for extra spare engines)
- Cost of new and used components
- Work-costs for disassembling the modules in the engine
- Work-costs for removing components from the modules
- Cost for repairing defective components
- Costs for testing the engine after maintenance

A mathematical optimization model for the whole engine, II

- Separate the modules before the components are disassembled

$$z_t^m \le \sum_{n\in\mathcal{A}^m} v_{nt} \quad t=1,\dots T, \quad m\in\mathcal{M}$$

$$v_{nt} \le v_{n't} \quad t=1,\dots,T, \quad n'\in\mathcal{A}(n),\ n\in\mathcal{A}$$

- Disassamble the components in the right order

$$x_{it}^m \le y_{it}^m \le z_t^m \le w_t \quad t=1,\dots,T, \quad i\in\mathcal{N}^m,\ m\in\mathcal{M}$$

$$\sum_{j\in\delta^m(i)} y_{jt}^m \ge y_{it}^m \quad t=1,\dots,T, \quad i\in\mathcal{N}^m,\ m\in\mathcal{M}$$

- The integrality requirements on the variables x_{it}^m and w_t may be removed—optimal solutions will be integer anyway

Decision variables for each time step $t=1,\dots,T$

$$x_{it}^m = \begin{cases}1, & \text{if component } i \text{ in module } m \text{ is replaced at } t\\ 0, & \text{otherwise}\end{cases} \quad i\in\mathcal{N}^m,\ m\in\mathcal{M}$$

$$y_{it}^m = \begin{cases}1, & \text{if component } i \text{ in module } m \text{ is removed at } t\\ 0, & \text{otherwise}\end{cases} \quad i\in\mathcal{N}^m,\ m\in\mathcal{M}$$

$$z_t^m = \begin{cases}1, & \text{if module } m \text{ is maintained at } t\\ 0, & \text{otherwise}\end{cases} \quad m\in\mathcal{M}$$

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

$$v_{nt} = \begin{cases}1, & \text{if activity } n \text{ is performed at } t\\ 0, & \text{otherwise}\end{cases} \quad n\in\mathcal{A}$$

Utilize an inventory of used spare parts

- New variables:

$$\tilde{x}_{ik}^m = \begin{cases}1, & \text{if } k\text{th used spare replaces component } i \text{ in module } m \text{ at time 1}\\ 0, & \text{otherwise}\end{cases}$$

- Constraints

$$\sum_{t=1}^{\overline{T}_i^m} x_{it}^m + \sum_{k\in\mathcal{K}_i^m} \tilde{x}_{ik}^m \ge 1, \quad i\in\mathcal{N}^m : \overline{T}_i^m \le T,\ m\in\mathcal{M}$$

$$\sum_{t=1}^{\tilde{T}_{ik}^m} x_{it}^m \ge \tilde{x}_{ik}^m, \quad k\in\mathcal{K}_i^m,\ i\in\mathcal{N}^m,\ m\in\mathcal{M}$$

$$\tilde{x}_{ik}^m \le y_{i1}^m, \quad k\in\mathcal{K}_i^m,\ i\in\mathcal{N}^m,\ m\in\mathcal{M}$$

- New objective function including spare parts' costs: minimize

$$\sum_{t=1}^{T}\left(\sum_{m\in\mathcal{M}}\left[\sum_{i\in\mathcal{N}^m}(c_{it}^m x_{it}^m + a_{it}^m y_{it}^m)\right] + d_t w_t + \sum_{n\in\mathcal{A}} b_{nt} v_{nt}\right) + \sum_{m\in\mathcal{M}}\sum_{i\in\mathcal{N}^m}\sum_{k\in\mathcal{K}_i^m} \tilde{c}_{ik}^m \tilde{x}_{ik}^m$$

Numerical tests for a whole engine

- The planning period (2500 flight hours) divided into 50–60–75 discrete time steps
- 7 modules, 61 components

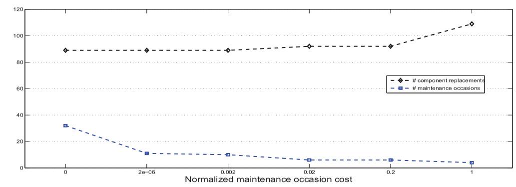
⇒ 3850–4620–5775 binary variables

- Costs and estimated lives for components
- Work costs for (dis)assembling modules and components

- Implemented in AMPL and solved using CPLEX

Varying the maintenance occasion cost d
An old engine, $T = 75$

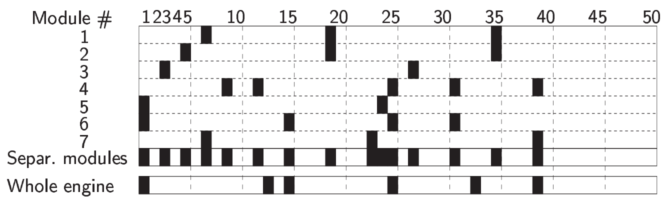
Maint. occ. cost (normalized)	# maint. occasions	# parts replaced	Total costs (normalized)	CPU-time (sec)
0	32	89	3.32	0.79
0.000002	11	89	3.32	1.17
0.002	10	89	3.34	2.23
0.02	6	92	3.48	1.95
0.2	6	92	4.56	22.71
1.0	4	109	8.01	14.83



Optimization over separate modules vs. the whole engine

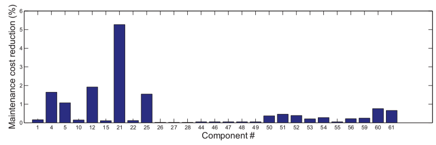
Old engine, $T = 50$

Optimization over	# maint. occasions	# replaced parts	Total costs (normalized)	cpu-time (sec)
separate modules	15	91	1.134	3.13
the whole engine	6	94	1.000	10.67

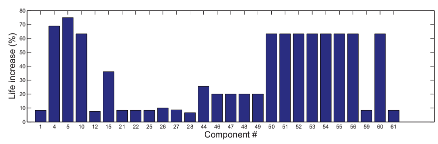


Beyond maintenance plans: Product development

- Potential reduction of total maintenance costs (in %) when a component's life is increased to its critical value



- Critical increase of life (in %) for the components

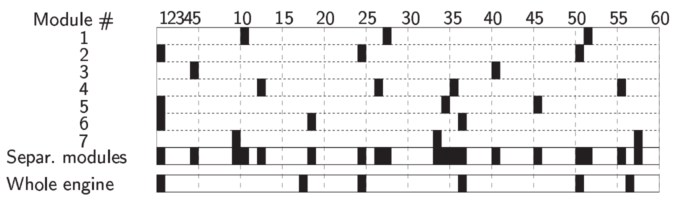


- Nine out of 61 components of RM12 have the potential to reduce maintenance costs $\geq 1\%$

Optimization over separate modules vs. the whole engine

Old engine, $T = 60$, remaining lives ≥ 15 at end of contract

Optimization over	# maint. occasions	# replaced parts	Total costs (normalized)	cpu-time (sec)
separate modules	19	90	1.151	3.08
the whole engine	6	92	0.942	1.25



Conclusions

- Opportunistic maintenance planning reduces costs for maintenance while retaining the functionality of the system at hand

- The more components, the more complicated to compute good schedules for maintenance

- Our quantitative optimization models and -methods are useful and computationally fairly tractable

- We are currently looking for more industrial cases within wind power generation and distribution, transportation and infrastructure, ...