Mathematics of maintenance planning optimization

Ann-Brith Strömberg

18 April 2008

The mathematical model for one module

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

$$z_t = \begin{cases} 1 & \text{if maintenance is made at time } t, \\ 0 & \text{otherwise,} \end{cases} \quad t = 1, \dots, T$$

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

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

Example

- Planning period $T = 7$
- Number of components $|\mathcal{N}| = 3$
- Life of components $T_1 = 3$, $T_2 = 5$, $T_3 = 6$

Replace each component before its life is over

- The components are new at time $t = 0$
- Life of component 1: $T_1 = 3$

$$\begin{aligned} x_{11} + x_{12} + x_{13} &\geq 1 \\ x_{12} + x_{13} + x_{14} &\geq 1 \\ x_{13} + x_{14} + x_{15} &\geq 1 \\ x_{14} + x_{15} + x_{16} &\geq 1 \\ x_{15} + x_{16} + x_{17} &\geq 1 \end{aligned}$$

- Life of component 2: $T_2 = 5$

$$\begin{aligned} x_{21} + x_{22} + x_{23} + x_{24} + x_{25} &\geq 1 \\ x_{22} + x_{23} + x_{24} + x_{25} + x_{26} &\geq 1 \\ x_{23} + x_{24} + x_{25} + x_{26} + x_{27} &\geq 1 \end{aligned}$$

- Life of component 3: $T_3 = 6$

$$\begin{aligned} x_{31} + x_{32} + x_{33} + x_{34} + x_{35} + x_{36} &\geq 1 \\ x_{32} + x_{33} + x_{34} + x_{35} + x_{36} + x_{37} &\geq 1 \end{aligned}$$

- Replace a component at time $t \Rightarrow$ The module is maintained at time t. For $t = 1, \dots, T$:

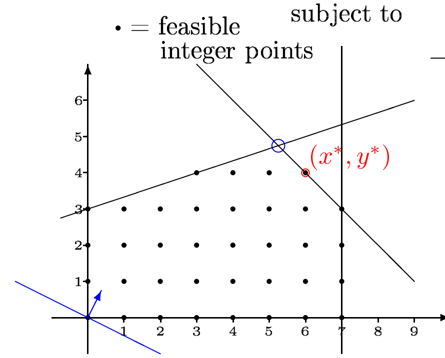
$$\begin{bmatrix} x_{1t} & & & \leq & z_t \\ & x_{2t} & & \leq & z_t \\ & & x_{3t} & \leq & z_t \end{bmatrix} \Leftrightarrow \begin{bmatrix} -x_{1t} & & & + z_t & \geq & 0 \\ & -x_{2t} & & + z_t & \geq & 0 \\ & & -x_{3t} & + z_t & \geq & 0 \end{bmatrix}$$

- Feasible set: $\{ \mathbf{x} \in B^{3 \cdot 7 + 7} \,|\, \mathbf{A}\mathbf{x} \geq \mathbf{b} \}$, where ....

```
      1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,1)
      0  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,2)
      0  0  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,3)
      0  0  0  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,4)
      0  0  0  0  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,5)
      0  0  0  0  0  0  0  1  1  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,6)
      0  0  0  0  0  0  0  0  1  1  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(1,7)
      0  0  0  0  0  0  0  0  0  1  1  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0            1          x(2,1)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  1  1  1  1  1  0  0  0  0  0  0  0  0            1          x(2,2)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  1  1  1  1  1  0  0  0  0  0  0  0            1          x(2,3)
     -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0            0          x(2,4)
      0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0            0          x(2,5)
      0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0            0          x(2,6)
      0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0            0          x(2,7)
      0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0            0          x(3,1)
A  =  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0      b  =  0      x  = x(3,2)
      0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1            0          x(3,3)
      0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0            0          x(3,4)
      0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0            0          x(3,5)
      0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0            0          x(3,6)
      0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0            0          x(3,7)
      0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0            0           z(1)
      0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0            0           z(2)
      0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  0  0  0  0  0  0  0  1            0           z(3)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1  0  0  0  0  0  0            0           z(4)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1  0  0  0  0  0            0           z(5)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1  0  0  0  0            0           z(6)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1  0  0  0            0           z(7)
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1  0  0            0
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1  0            0
      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 -1  0  0  0  0  0  0  1            0
```


An integer linear program

$$
\begin{array}{lrcrcll}
\text{maximize} & x & + & 2y & & & \\
\text{subject to} & x & + & y & \leq & 10 & (1) \\
 & -x & + & 3y & \leq & 9 & (2) \\
 & x & & & \leq & 7 & (3) \\
 & & & x, y & \geq & 0 & (4,5) \\
 & & & x, y & & \text{integer} &
\end{array}
$$



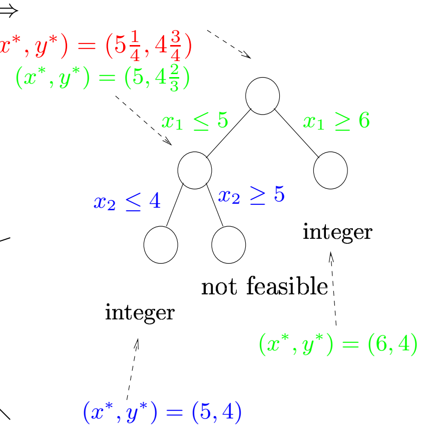
$$(x^*, y^*) = \begin{pmatrix} 6 \\ 4 \end{pmatrix}$$

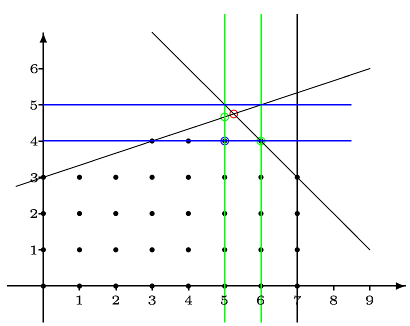
(The optimal extreme point to the continuous model is fractional)

Branch and bound (in e.g. Cplex)

Relax integrality requirements ⇒
linear, continuous problem ⇒ $(x^*, y^*) = (5\frac{1}{4}, 4\frac{3}{4})$

Search tree: branch over
fractional variable values





In the worst case ...

- It is reasonable to assume $T \approx 50$ time steps (or more)

⇒ 50 integer variables: $z_0, \ldots, z_{49}$

⇒ $2^{50} \approx 10^{15}$ branches

- Solve one continuous problem in 10^{-6} seconds ⇒ 10^9seconds ≈ 30 years (10^{-9} seconds ⇒ ≈ 1.5 weeks)

- It is not really this bad for us, but:

  Better to generate facets so that all extreme points become integral

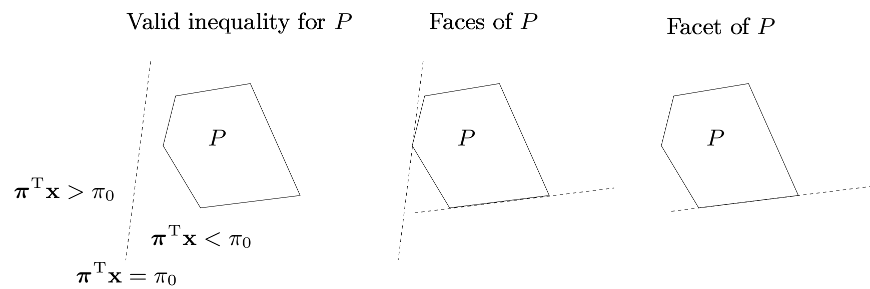
  A facet is a “best possible” cutting plane

The smallest polyhedron containing all feasible points

- A general polyhedron defined by linear inequalities:
  $S = \left\{ \mathbf{x} \in \Re^n \,\middle|\, \mathbf{A}^{\mathrm{T}}\mathbf{x} \geq \mathbf{b} \right\}$
- The integer points of a (bounded) polyhedron defined by linear inequalities:
  $S_{\text{int}} = \left\{ \mathbf{x} \in \Re^n \,\middle|\, \mathbf{A}^{\mathrm{T}}\mathbf{x} \geq \mathbf{b}, \text{integral} \right\} = \left\{ \mathbf{x}^1, \mathbf{x}^2, \ldots, \mathbf{x}^K \right\}$
- We would like to find the convex hull of S_{int}: $P = \mathtt{conv} S_{\text{int}} =$
  $$\left\{ \mathbf{x} \in \Re^n \;\middle|\; \mathbf{x} = \sum_{k=1}^{K} \alpha_k \mathbf{x}^k, \quad \sum_{k=1}^{K} \alpha_k = 1, \quad \alpha_k \geq 0, k = 1, \ldots, K \right\}$$
- $P \subseteq S$ is also a polyhedron
- It then holds that $\min_{\mathbf{x} \in S_{\text{int}}} \mathbf{c}^{\mathrm{T}}\mathbf{x} = \min_{\mathbf{x} \in P} \mathbf{c}^{\mathrm{T}}\mathbf{x}$
- DRAW THE CONVEX HULL OF THE INTEGER POINTS!!

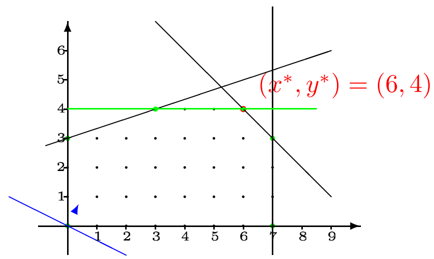
Valid inequalities, faces and facets

- $\boldsymbol{\pi}^{\mathrm{T}}\mathbf{x} \leq \pi_0$ is a *valid inequality* for P if it holds for all $\mathbf{x} \in P$
- *Face*: $F = \left\{ \mathbf{x} \in P \,\middle|\, \boldsymbol{\pi}^{\mathrm{T}}\mathbf{x} = \pi_0 \right\}$ if $\boldsymbol{\pi}^{\mathrm{T}}\mathbf{x} \leq \pi_0$ is a valid ineq. for P
- *Facet*: face of dimension $n - 1$



For the small example

- Find all facets ⇒ no integrality requirements needed



A class of maintenance facets

For the components p and q such that the lives T_p and T_q fulfil

$$2 \leq T_q \leq T_p - 1 \leq 2 \cdot (T_q - 1)$$

a class of facets is defined by:

$$z_\ell + \sum_{t=\ell+1}^{\ell+T_p-2} (x_{pt} + x_{qt}) + z_{\ell+T_p-1} \geq 2, \qquad \ell = 1, \ldots, T - T_p + 1.$$

For the example ($T_1 = 3$, $T_2 = 5 \Rightarrow p = 2$, $q = 1$):

$$2 \leq T_1 = 3 \leq T_2 - 1 = 4 \leq 2 \cdot (T_1 - 1) = 4$$

A facet is given by the inequality

$$z_2 + x_{13} + x_{14} + x_{15} + x_{23} + x_{24} + x_{25} + z_6 \geq 2$$

Construction of a valid inequality

$$\begin{aligned} x_{12}+x_{13}+x_{14} &\geq 1 \\ x_{14}+x_{15}+x_{16} &\geq 1 \\ x_{22}+x_{23}+x_{24}+x_{25}+x_{26} &\geq 1 \end{aligned}$$

Aggregate $\Rightarrow$ $x_{12}+x_{13}+2x_{14}+x_{15}+x_{16}+x_{22}+x_{23}+x_{24}+x_{25}+x_{26} \geq 3$ (1)

$$\begin{aligned} z_2 &\geq x_{12} \\ z_6 &\geq x_{16} \\ z_2 &\geq x_{22} \\ z_6 &\geq x_{26} \end{aligned}$$

Aggregate $\Rightarrow$ $2z_2 + 2z_6 \geq x_{12} + x_{16} + x_{22} + x_{26}$ (2)

(1) and (2) $\Rightarrow$ $2z_2 + x_{13} + 2x_{14} + x_{15} + x_{23} + x_{24} + x_{25} + 2z_6 \geq 3$ (3)

Construction cont'd

Multiply (3) by $\frac{1}{2}$:

$z_2 + x_{13} + x_{14} + \frac{1}{2}x_{15} + \frac{1}{2}x_{23} + \frac{1}{2}x_{24} + \frac{1}{2}x_{25} + z_6 \geq \frac{3}{2}$ (4)

Round-up the coefficients of the LHS to the nearest integer (OK?!):

$z_2 + x_{13} + x_{14} + x_{15} + x_{23} + x_{24} + x_{25} + z_6 \geq \frac{3}{2}$

All numbers in the LHS are integral in a feasible solution to the integer program $\Rightarrow$ Round-up the RHS to the nearest integer:

$z_2 + x_{13} + x_{14} + x_{15} + x_{23} + x_{24} + x_{25} + z_6 \geq 2$

We have shown that this inequality is *valid* for the *maintenance polytope.*

To show that it defines a *facet* takes a little more ...