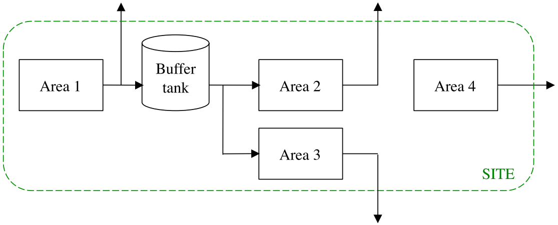
On/off production modeling



- Utilities and areas are considered to be either operating or not operating, i.e. ’on’ or ’off’.
- An area operates at maximum production speed when available, and does not operate when not available.
- Including or not including buffer tanks between areas.

UDM: On/off without buffer tanks

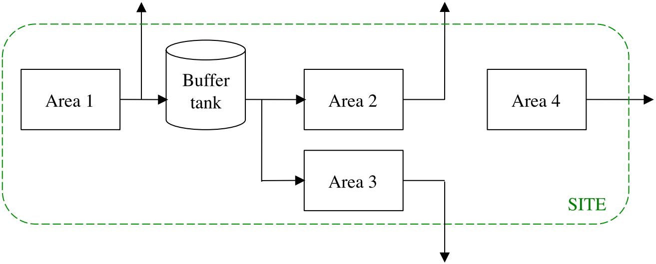
Use utility and area availabilities to estimate revenue loss

+ Simple modeling; Only need to know which utilities that are required by each area and how areas are connected
+ Orders utilities according to the revenue loss they cause
+ Worst case estimates of revenue losses

– Greatly overestimates the revenue losses
– Only information about WHICH utilities that cause large losses, no information on HOW to improve the availabilities of these utilities
– Internal buffer tanks not included $\Rightarrow$ No decision support for choosing buffer tank levels
– No dynamics included $\Rightarrow$ No reactive disturbance management strategies may be obtained

Matrix representation

Representation of the interconnection of production areas



Area dependence matrix

$$A_d = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(size $n_a \times n_a$)

Matrix representation

Representation of utility measurement data

$$
\begin{array}{ll}
\text{steam} = & [42 \quad 38 \quad 34 \quad 32 \quad 35 \quad 41 \quad 40 \quad 36 \quad 34 \quad 37] \\
\text{cooling water} = & [25 \quad 24 \quad 24 \quad 26 \quad 28 \quad 30 \quad 27 \quad 25 \quad 24 \quad 25] \\
\text{electricity} = & [1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 1] \\
\text{feed water} = & [22 \quad 19 \quad 18 \quad 20 \quad 22 \quad 21 \quad 21 \quad 21 \quad 21 \quad 21] \\
\text{instrument air} = & [1 \quad 2 \quad 1 \quad 1 \quad 3 \quad 2 \quad 1 \quad 0 \quad 0 \quad 1]
\end{array}
$$

Disturbance limits:

$$
\begin{array}{ll}
\text{Steam :} & \text{pressure} < 35 \text{ bar} \\
\text{Cooling water :} & \text{temperature} > 27^\circ\text{C} \\
\text{Electricity :} & \text{on/off} \\
\text{Feed water :} & \text{pressure} < 20 \text{ bar} \\
\text{Instrument air :} & \text{pressure} \leq 0 \text{ bar}
\end{array}
$$

Matrix representation

Utility operation matrix

$$U = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

(size $n_u \times n_s$)

Matrix representation

Utility requirements

	Area 1	Area 2	Area 3	Area 4
Steam	x		x	
Cooling water		x	x	
Electricity	x	x	x	x
Feed water	x		x	
Instrument air	x		x	x

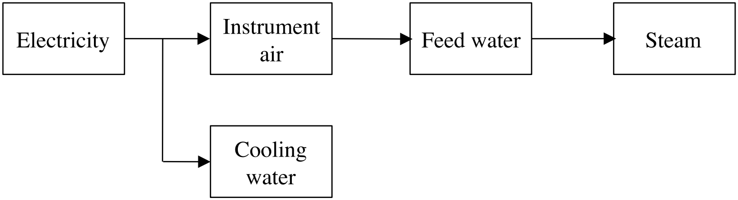
Area-utility matrix

$$A_u = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix}$$

(size $n_a \times n_u$)

Matrix representation

Utility dependence



Utility dependence matrix

$$U_d = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix}$$

(size $n_u \times n_u$)

UDM calculations using matrix representation

Using only the general matrix representation, it is possible to:

- Remove utility dependence
- Compute utility availability
- Compute direct and total area availability
- Estimate revenue losses for areas and utilities

Notation

First, some notation:

n_a number of areas

n_b number of buffer tanks

n_u number of utilities

n_s number of samples

t_s sampling time

$p = \begin{bmatrix} p_1 & p_2 & \dots & p_{n_a} \end{bmatrix}^T$ contribution margins

$q = \begin{bmatrix} q_1 & q_2 & \dots & q_{n_a} \end{bmatrix}^T$ production

$q^m = \begin{bmatrix} q_1^m & q_2^m & \dots & q_{n_b}^m \end{bmatrix}^T$ flows to the market

$V = \begin{bmatrix} V_1 & V_2 & \dots & V_{n_b} \end{bmatrix}^T$ buffer tank levels

Notation

More notation:

$$\mathbf{1}\mathbf{1}^T = \begin{bmatrix} 1 \\ 1 \\ \dots \\ 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 & \dots & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & 1 & \dots & 1 \\ \vdots & \vdots & \ddots & 1 \\ 1 & 1 & \dots & 1 \end{bmatrix}$$

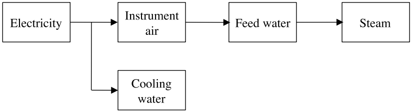
$$\text{sign}(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x = 0 \\ -1 & x \leq 0 \end{cases}$$

Remove utility dependence

Remove utility dependence from U

$$U_{ud} = \text{sign}\left(U + \text{sign}\left((I - U_d)(U - \mathbf{1}\mathbf{1}^T)\right)\right)$$

$$U_d = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix}$$



$$U = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Remove utility dependence

$$U_{ud} = \text{sign}\left(U + \text{sign}\left((I - U_d)(U - \mathbf{1}\mathbf{1}^T)\right)\right)$$

$$(I - U_d)(U - \mathbf{1}\mathbf{1}^T) = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$U = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$$U_{ud} = \begin{bmatrix} 1 & 1 & \color{red}{1} & 0 & 1 & 1 & 1 & 1 & \color{red}{1} & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Compute utility availability

Utility Availability

$$U_{av} = U \cdot \mathbf{1} / n_s$$

$$U = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix} \quad U_{ud} = \begin{bmatrix} 1 & 1 & \underline{1} & 0 & 1 & 1 & 1 & 1 & \underline{1} & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$$U_{av} = \begin{bmatrix} 0.7 & 0.8 & 0.9 & 0.8 & 0.8 \end{bmatrix}^T \quad U_{av}^{ud} = \begin{bmatrix} 0.9 & 0.8 & 0.9 & 0.8 & 0.8 \end{bmatrix}^T$$

Compute direct area availability

Direct area availability

$$A_{av}^{dir} = A_{dir} \cdot \mathbf{1}/n_s$$
$$A_{dir} = \mathbf{1}\mathbf{1}^T + \text{sign}\left(A_u(U - \mathbf{1}\mathbf{1}^T)\right)$$

$$A_u = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix}$$

$$A_uU = \begin{bmatrix} 4 & 3 & 2 & 3 & 4 & 4 & 3 & 3 & 2 & 4 \\ 2 & 2 & 2 & 2 & 1 & 1 & 1 & 2 & 2 & 2 \\ 5 & 4 & 3 & 4 & 4 & 4 & 4 & 4 & 3 & 5 \\ 2 & 2 & 2 & 2 & 2 & 2 & 1 & 1 & 1 & 2 \end{bmatrix}$$

$$A_{dir} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Compute direct area availability

$$A_{dir} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_{av}^{dir} = A_{dir} \cdot \mathbf{1}/n_s = \begin{bmatrix} 0.4 & 0.7 & 0.2 & 0.7 \end{bmatrix}^T$$

Compute total area availability

Total area availability

$$A_{av}^{tot} = A_{tot} \cdot \mathbf{1}/n_s$$
$$A_{tot} = \mathbf{1}\mathbf{1}^T + \text{sign}\left(A_d(A_{dir} - \mathbf{1}\mathbf{1}^T)\right)$$

$$A_d = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_d A_{dir} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 2 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 2 \\ 2 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 2 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_{tot} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Compute total area availability

$$A_{tot} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_{av}^{tot} = A_{tot} \cdot \mathbf{1}/n_s = \begin{bmatrix} 0.4 & 0.2 & 0.2 & 0.7 \end{bmatrix}^T$$

Estimation of direct revenue loss in each area

Direct revenue loss in each area

$$J_p^{dir} = \left(\mathbf{1} - A_{av}^{dir}\right) .* q^m .* p n_s t_s$$

With $q^m = \begin{bmatrix} 1 & 2 & 1 & 3 \end{bmatrix}^T$, $p = \begin{bmatrix} 1 & 2 & 4 & 1 \end{bmatrix}^T$, $t_s = 1$ we get:

$$J_p^{dir} = \left[\begin{array}{cccc} 6 & 12 & 32 & 9 \end{array} \right]^T$$

Estimation of total revenue loss in each area

Total revenue loss in each area

$$J_p^{tot} = \left(\mathbf{1} - A_{av}^{tot}\right) .* q^m .* p n_s t_s$$

With $q^m = \begin{bmatrix} 1 & 2 & 1 & 3 \end{bmatrix}^T$, $p = \begin{bmatrix} 1 & 2 & 4 & 1 \end{bmatrix}^T$, $t_s = 1$ we get:

$$J_p^{tot} = \left[\begin{array}{cccc} 6 & 32 & 32 & 9 \end{array} \right]^T$$

Estimation of direct revenue loss due to each utility

Direct revenue loss due to utilities

$$J_u^{dir} = \text{diag}\left[\mathbf{1} - U_{av}^{ud}\right] \cdot A_u^T (q^m .* p) n_s t_s$$

$$\text{diag}\left[\mathbf{1} - U_{av}^{ud}\right] \cdot A_u^T = \begin{bmatrix} 0.1 & 0 & 0.1 & 0 \\ 0 & 0.2 & 0.2 & 0 \\ 0.1 & 0.1 & 0.1 & 0.1 \\ 0.2 & 0 & 0.2 & 0 \\ 0.2 & 0 & 0.2 & 0.2 \end{bmatrix}$$

With $q^m = \begin{bmatrix} 1 & 2 & 1 & 3 \end{bmatrix}^T, p = \begin{bmatrix} 1 & 2 & 4 & 1 \end{bmatrix}^T, t_s = 1$:

$$J_u^{dir} = \begin{bmatrix} 5 & 16 & 12 & 10 & 16 \end{bmatrix}^T$$

Estimation of total revenue loss due to each utility

Total revenue loss due to utilities

$$J_u^{tot} = \text{diag}\left[\mathbf{1} - U_{av}^{ud}\right] \cdot \text{sign}\left(A_d A_u\right)^T (q^m . * p) n_s t_s$$

$$\text{diag}\left[\mathbf{1} - U_{av}^{ud}\right] \cdot \text{sign}\left(A_d A_u\right)^T = \begin{bmatrix} 0.1 & 0.1 & 0.1 & 0 \\ 0 & 0.2 & 0.2 & 0 \\ 0.1 & 0.1 & 0.1 & 0.1 \\ 0.2 & 0.2 & 0.2 & 0 \\ 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix}$$

With $q^m = \begin{bmatrix} 1 & 2 & 1 & 3 \end{bmatrix}^T$, $p = \begin{bmatrix} 1 & 2 & 4 & 1 \end{bmatrix}^T$, $t_s = 1$:

$$J_u^{tot} = \begin{bmatrix} 9 & 16 & 12 & 18 & 24 \end{bmatrix}^T$$