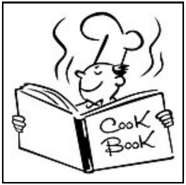
Utility Disturbance Management in the Process Industry

Based on the PhD Thesis by Anna Lindholm

Market-driven Systems, May 22, 2014

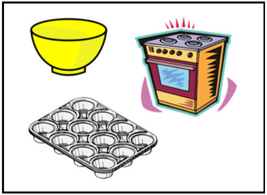
Utilities

"*Utilities – Support processes that are utilized in production, but are not part of the final product.*"

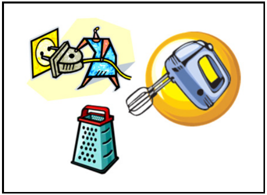


Raw material

Equipment



Utilities

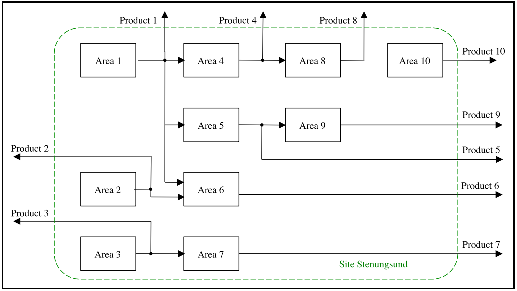


Utilities in the process industry

"*Utilities – Support processes that are utilized in production, but are not part of the final product.*"

- Steam
- Cooling water
- Electricity
- Fuel
- Water treatment
- Combustion of tail gas
- Nitrogen
- Water
- Compressed air
- Vacuum system

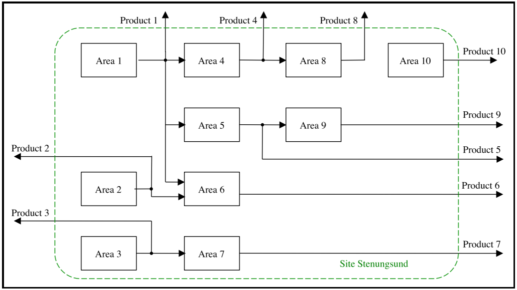
A process industrial site



Why disturbances in utilities?

Disturbances in utilities

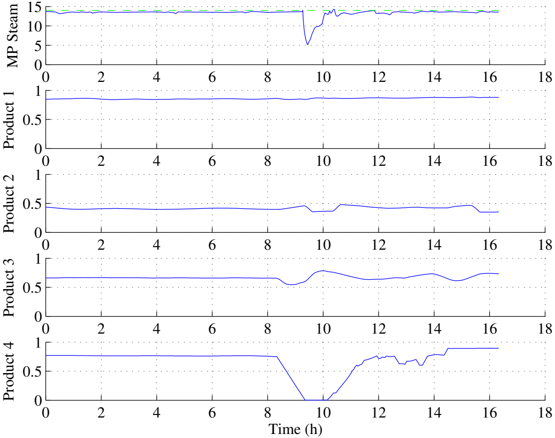
- affect many areas at a site, directly or indirectly
- are common within the process industry



Also, root cause hard to determine because of utility interdependence.

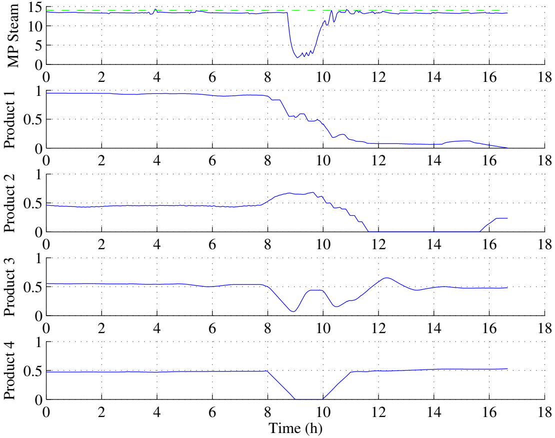
An industrial example (1)

Example 1: Pressure drop in middle-pressure steam net



An industrial example (2)

Example 2: Pressure drop in middle-pressure steam net



Objective

Use a method for utility disturbance management to achieve

- information on which utilities that cause large revenue losses at a site.
- strategies for how to control the production at a disturbance to minimize the loss of revenue.

Outline

- Disturbance management
- Disturbances in utilities
- Performance indicators
- The UDM method
- On/Off production modeling
- Matrix representation
- Case study at Perstorp
- Continuous production modeling
- Optimizing supply of utilities

Disturbance management

Proactive disturbance management

Disturbance management strategies that are aiming to prevent future disturbance occurrences.

Reactive disturbance management

Disturbance management strategies for handling disturbances when they occur.

Disturbances in utilities

No negative effect on production as long as the utility operates within limits.

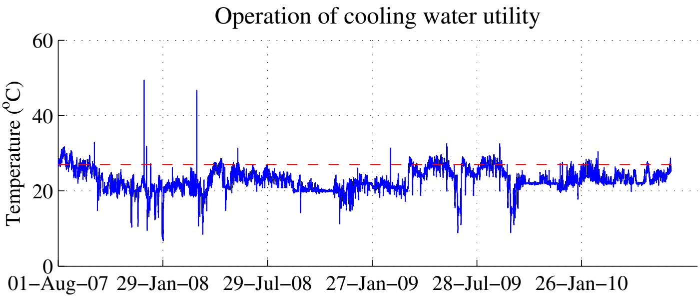
Suggestion: Set limits for when a disturbance in a utility has negative impact on the production.

- Steam: Steam pressure outside certain limits
- Cooling water: Cooling water temperature outside certain limits
- ...

$\Rightarrow$ Utility disturbances can be identified from measurement data.

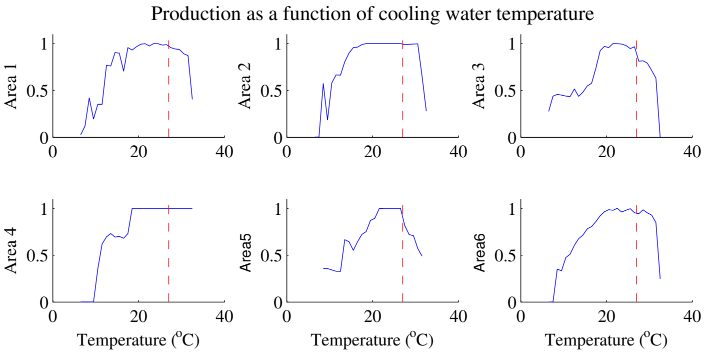
Disturbances in utilities – Example

Example: Cooling water temperature



Validation of limits

Example: Cooling water temperature



Utility availability

Definition

Utility availability is the fraction of time all utility parameters are inside their critical limits.

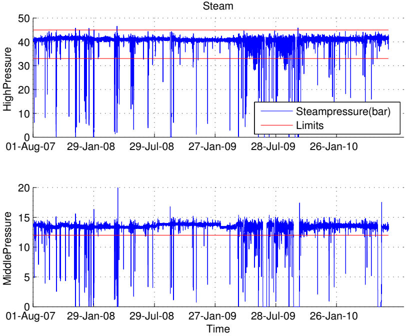
Availability computations

Example: Steam

Disturbance limits, pressure p:

High pressure steam: $p < 33$ bar or $p > 45$ bar

Middle pressure steam: $p < 12$ bar



Steam availability = 95.94 %

Utilities required at each area

Each area at a site requires a specific set of utilities.

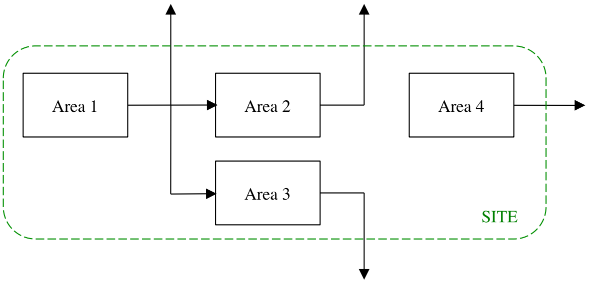
	Area 1	Area 2	Area 3	Area 4
Steam	x	x		
Cooling water	x	x	x	x
Electricity	x	x	x	x
Fuel	x			
Water treatment utility		x		x
Combustion of tail gas	x	x		
Nitrogen	x	x	x	x
Water	x	x	x	x
Compressed air	x	x	x	x
Vacuum system	x	x	x	

Area availability

Definition

The *direct area availability* is the fraction of time all utility parameters for all utilities needed at an area are inside their critical limits.

Area interdependence



Definition

The *total area availability* is the fraction of time all utility parameters for all utilities needed at an area are inside their critical limits

AND

all areas which the area is dependent on are available.

The UDM method

Utility Disturbance Management (UDM) method

A) Estimate the revenue loss caused by each utility at the site

B) Reduce the revenue loss due to future disturbances in utilities

The UDM method – Step by step

1. Get information on site-structure and utilities
2. Compute utility and area availabilities
3. Estimate revenue loss due to disturbances in utilities
4. Reduce revenue loss due to future disturbances in utilities

Step 1 of the UDM method

Get information on site structure and utilities

a) Depict the overall structure of the site
b) List all utilities used at the site
c) Determine which utilities that are required at each area
d) Draw a utility dependence flowchart
e) Define disturbance limits for each utility
f) Get relevant measurement data
g) List all planned stops during the time period

Step 2 of the UDM method

Compute utility and area availabilities

a) Compute utility availabilities
b) Compute direct and total area availabilities

Step 3 of the UDM method

Estimate revenue loss due to disturbances in utilities

a) Select site model
b) Estimate flow to the market of each product
c) Get contribution margins for each product
d) Estimate revenue loss for each product
e) Estimate revenue loss due to each utility

Step 3 d) and 3 e) are dependent on the choice of modeling approach.

Step 4 of the UDM method

Reduce revenue loss due to future disturbances in utilities

This step is dependent on the choice of modeling approach.

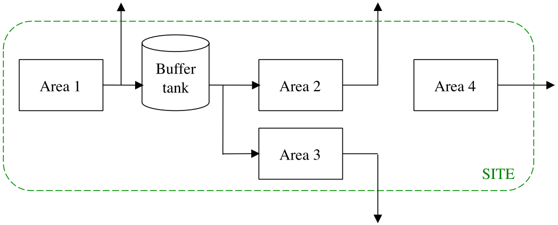
The step results in

- proactive disturbance management strategies

  and/or

- reactive disturbance management strategies

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

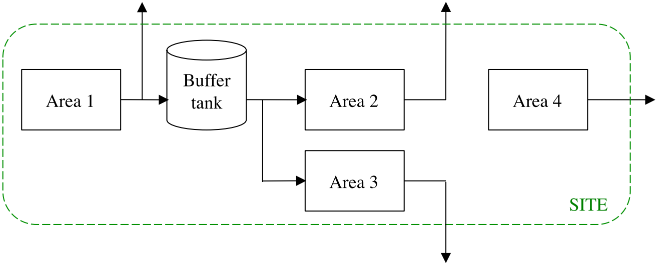
Use utility and area availabilities to estimate revenue loss

+ 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 ⇒ No decision support for choosing buffer tank levels
– No dynamics included ⇒ 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

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

Disturbance limits:

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

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

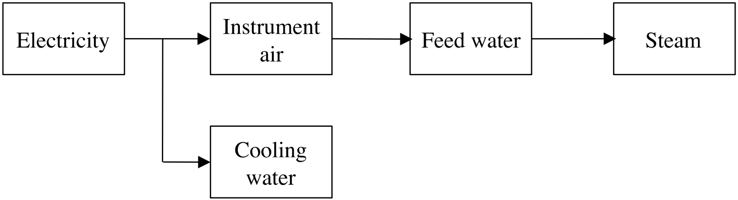
Area-utility matrix

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

(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:

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

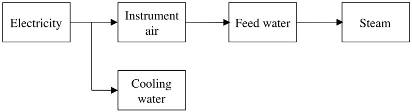
$$\mathrm{sign}(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x = 0 \\ -1 & x \leq 0 \end{cases}$$

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

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

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

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

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

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

$$A_{av}^{tot} = A_{tot} \cdot \mathbf{1}/n_s$$

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

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

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

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

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

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

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

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

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

Case study at Perstorp

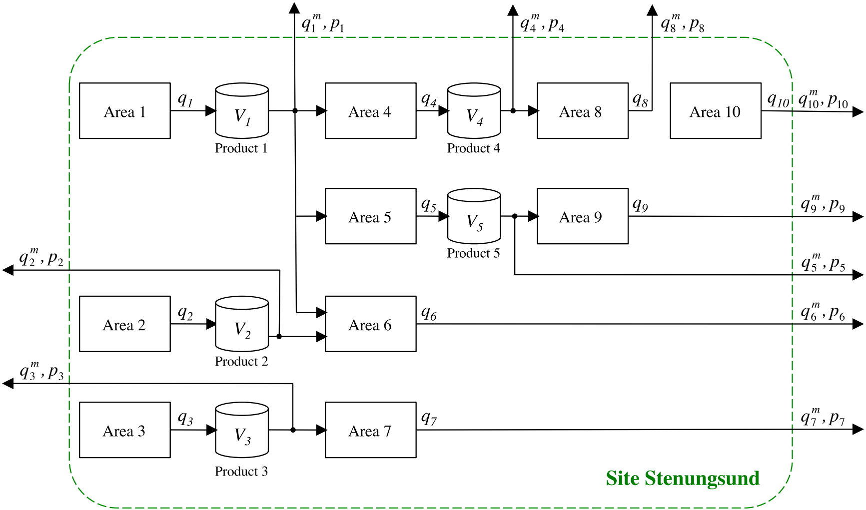
- UDM method applied to site Stenungsund, Perstorp
- On/off production modeling without buffer tanks

Site Stenungsund Located on the Swedish west coast, 50 km north of Gothenburg.

Main products: Aldehydes, organic acids, alcohols, plasticizers

Perstorp
WINNING FORMULAS

Flowchart of the product flow



Utility requirements

	1	2	3	4	5	6	7	8	9	10
Steam HP							x	x	x	x
Steam MP	x	x	x	x	x	x	x		x	
Cooling water	x	x	x	x	x	x	x	x	x	x
Cooling fan 1	x									
Cooling fan 2		x								
Cooling fan 3			x							
Cooling fan 7							x			
Electricity	x	x	x	x	x	x	x	x	x	x
Water treatment	x	x	x	x	x	x		x	x	
Flare	x	x	x	x	x	x				x
Combustion device 7							x			
Combustion device 9									x	
Nitrogen	x	x	x	x	x	x	x	x	x	x
Feed water	x	x	x	x	x			x		
Instrument air	x	x	x	x	x	x	x	x	x	x

Summary of case study problem

- 10 production areas
- 15 utilities
- 5 internal buffer tanks
- August 1, 2007 – July 1, 2010
- Planned stop September 15 – October 8, 2009
- Sampling interval 1 minute

$\Rightarrow$ Size $15 \times 1\ 501\ 921$ of the utility operation matrix

Case study matrices

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

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

Estimates of revenue losses caused by each utility

Direct loss	Total loss
Cooling water	Cooling water
MP steam	MP steam
Combustion device 9	Cooling fan 1
Combustion device 7	Feed water
Cooling fan 1	Combustion device 9
Electricity	Combustion device 7
HP steam	Electricity
Feed water	HP steam
Nitrogen	Cooling fan 2
Cooling fan 3	Cooling fan 3
Cooling fan 2	Nitrogen
Instrument air	Instrument air
Cooling fan 7	Cooling fan 7
Flare	Flare
Water treatment	Water treatment

Case study conclusions

- The cooling water utility seems to cause the greatest losses at site Stenungsund
- Proactive disturbance management:
  - Improve availability of cooling water utility

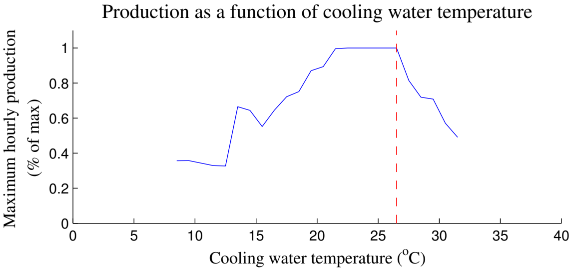
Remaining question: How should disturbances in the supply of utilities be handled, when they occur?

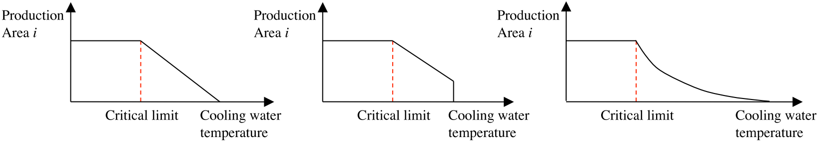
Continuous production modeling

- Effects of disturbances in utilities on production
- Shared utilities (+connections of areas via the product flow)

Continuous production modeling I

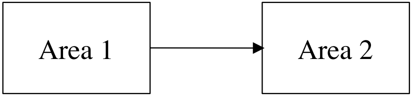
Effects of disturbances in utilities on production





Continuous production modeling II

Connections of areas via the product flow (shared utilities)



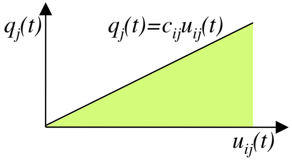
Idea: Separate modeling of utility effects on production from optimization problem (optimal supply of utilities to each area).'

Represent utilities as volumes that are shared by all areas that require them.

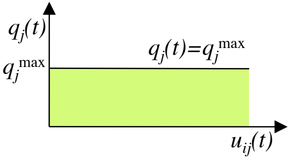
Modeling of utilities

Two main types of utilities:

Continuous



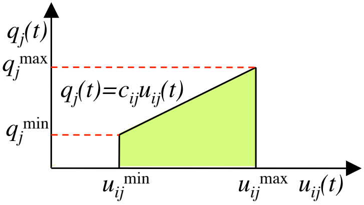
On/off

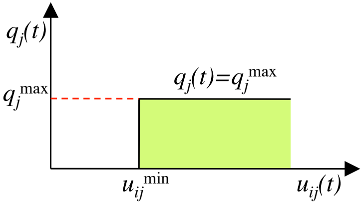


$$q_j \leq c_{ij} u_{ij} + m_{ij}$$

Modeling of utilities

With maximum and minimum constraints on production:



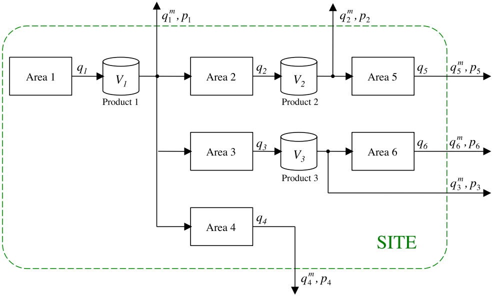


Shared utilities

Utilities are shared between production areas:

$$\sum_j u_{ij} \leq U_i, \quad i = 1, \ldots, n_u$$

Formulation of optimization problem



Site model (mass balance)

$$V_1(t+1) = V_1(t) + q_1(t) - q_1^m(t) - q_2^{\text{in}}(t) - q_3^{\text{in}}(t) - q_4^{\text{in}}(t)$$

$$V_2(t+1) = V_2(t) + q_2(t) - q_2^m(t) - q_5^{\text{in}}(t)$$

$$V_3(t+1) = V_3(t) + q_3(t) - q_3^m(t) - q_6^{\text{in}}(t)$$

Formulation of optimization problem

Constraints on buffer tanks

$$
\begin{aligned}
V_1^{\min} &\leq V_1(t) \leq V_1^{\max} \\
V_2^{\min} &\leq V_2(t) \leq V_2^{\max} \\
V_3^{\min} &\leq V_3(t) \leq V_3^{\max}
\end{aligned}
$$

Formulation of optimization problem

Constraints on production rates

$$q_i^{\min} \leq q_i(t) \leq q_i^{\max}$$

or

Constraints on production rates

$$q_i^{\min} + s_i(t) \leq q_i(t) \leq q_i^{\max}$$
$$-q_i^{\min} \leq s_i(t) \leq 0$$

if shutdown/start-up of areas should be penalized.

Formulation of optimization problem

Constraints due to shared utilities

$$\sum_{j \in \mathcal{M}_i} u_{ij}(t) \leq U_i(t), \quad i = 1, \ldots, n_u$$

$$q_j(t) \leq c_{ij} u_{ij}(t) + m_{ij}$$

Continuous

$$\sum_{j \in \mathcal{M}_i} \frac{1}{c_{ij}} q_j(t) - \frac{m_{ij}}{c_{ij}} \leq U_i(t)$$

On/off

$$q_j(t) \leq \begin{cases} q_j^{\max} & \text{if } U_i(t) = 1 \\ 0 & \text{if } U_i(t) = 0, \end{cases} \qquad j \in \mathcal{M}_i$$

Formulation of optimization problem

Area $\rightarrow$	1	2	3	4	5	6
Steam HP	x		x			
Steam MP		x		x		x
Cooling water	x	x	x	x	x	x

Constraints due to shared utilities

$$\frac{1}{c_{11}} q_1(t) + \frac{1}{c_{13}} q_3(t) \leq U_1(t)$$

$$\frac{1}{c_{22}} q_2(t) + \frac{1}{c_{24}} q_4(t) + \frac{1}{c_{26}} q_6(t) \leq U_2(t)$$

$$\sum_{i=1}^{6} \frac{1}{c_{3i}} q_i(t) \leq U_3(t)$$

Formulation of optimization problem

Steady-state optimization

Optimal steady-state operation determined from linear program:

$$\text{maximize} \sum_{q,q^m}^{n_a} p^T q^m$$
$$\text{subject to constraints}$$

$\Rightarrow$ Optimal profit p_{ref}, optimal production rates q_{ref}, optimal flows to market q^m_{ref} in steady state.

Formulation of optimization problem

Dynamic optimization

Minimize deviation from optimal steady-state operation.

Cost function (e.g.):

$$J_t = (p^T q^m(t) - p_{ref})^2 Q_p + \Delta V^T(t) Q \Delta V(t) + \Delta q^T(t) R \Delta q(t)$$

where

$$\Delta V(t) = V(t) - V_{ref}$$
$$\Delta q(t) = q(t) - q_{ref}$$

Add terms $-g^T s(t) + s^T(t) Q_s s(t)$ if shutdown of areas should be penalized.

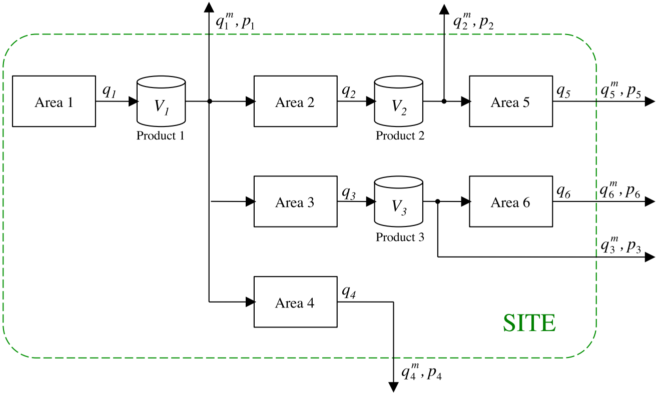
Formulation of optimization problem

Dynamic optimization

$$\text{minimize} \sum_{\tau=0}^{N-1} J_t\left(q(\tau), q^m(\tau), V(\tau), s(\tau)\right)$$
$$\text{subject to constraints}$$

For online disturbance management, the optimization problem may be solved in receding horizon fashion (MPC).

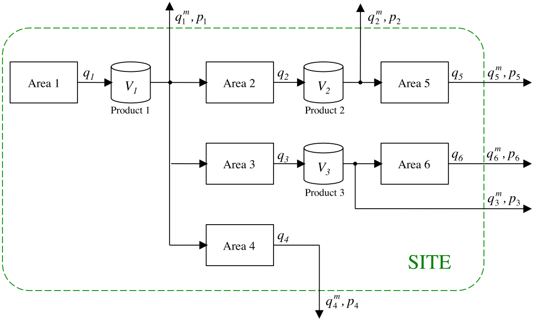
An example



Assume utilities are shared equally at maximum production. How should utility resources be divided when a disturbance in a utility occurs?

An example

	$q^{\max}$	p
Product 1	1	0.4
Product 2	0.5	0.7
Product 3	0.2	0.1
Product 4	0.1	0.5
Product 5	0.2	0.8
Product 6	0.2	1.0



Solution to steady state optimization problem

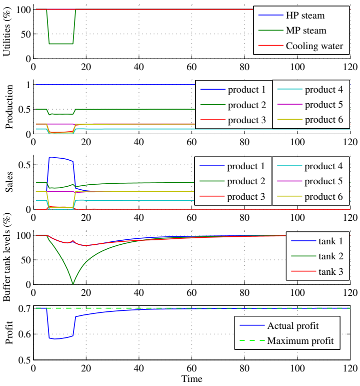
$$q_{\text{ref}} = \begin{bmatrix} 1 & 0.5 & 0.2 & 0.1 & 0.2 & 0.2 \end{bmatrix}^T$$

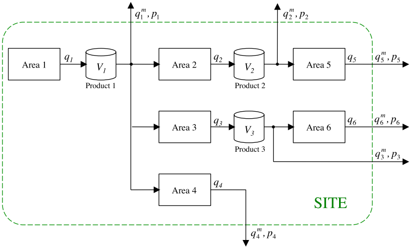
$$q^m_{\text{ref}} = \begin{bmatrix} 0.2 & 0.3 & 0 & 0.1 & 0.2 & 0.2 \end{bmatrix}^T$$

with the optimal profit $p_{\text{ref}} = 0.7$.

Solution to dynamic optimization problem

MP steam disturbance

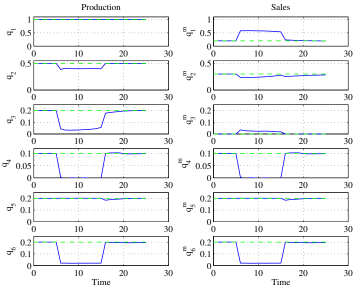


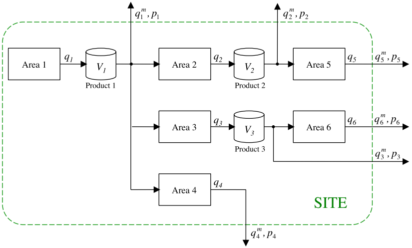


MP steam affects area 2, 4 and 6.

Solution to dynamic optimization problem

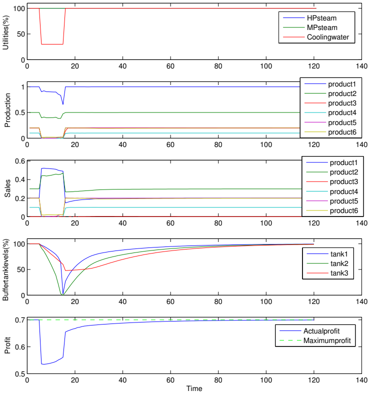
MP steam disturbance

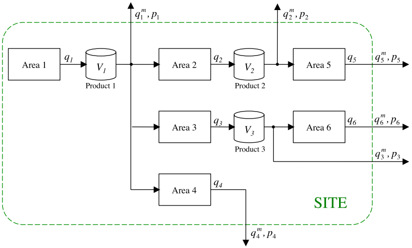




Solution to dynamic optimization problem

Cooling water disturbance

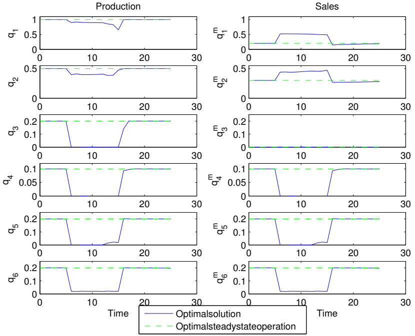


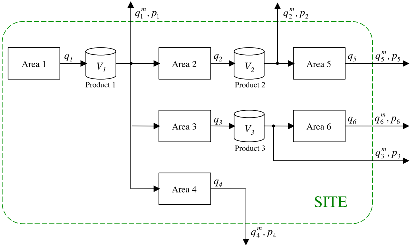


Cooling water affects all areas.

Solution to dynamic optimization problem

Cooling water disturbance





UDM: Continuous production modeling

Continuous representation of utilities and areas.

+ Find and evaluate reactive disturbance management strategies
+ Process understanding by simulations
+ MPC as a tool for online disturbance management

– Much modeling effort needed
– Could be hard to identify utilities effect on production

Summary

- Disturbances in utilities cause great losses at industrial sites.
- Their effect is hard to predict since they are shared between production areas, that are connected by the product flow.
- The UDM method is a general method for utility disturbance management.
- The UDM method with on/off production modeling is a tool for quickly ordering the utilities at a site according to the loss they cause. The computations can be carried out efficiently using a matrix representation.
- The UDM method with continuous production modeling gives both proactive and reactive disturbance management strategies. MPC may be used for online disturbance management.

Documentation

- A General Method for Handling Disturbances on Utilities in the Process Industry, Anna Lundholm, Hampus Carlsson, Charlotta Johnsson, 18th IFAC World Congress, Milamo, Italy, 2011 (the general idea, motivation)
- A Tool for Utility Disturbance Management, Anna Lundholm, Charlotta Johnsson, 14th IFAC Symposium on Information Control Problems in Manufacturing, Bucharest, Romania, May 2012 (the on/off model case)
- Formulating an Optimization Problem for Minimization of Losses due to Utilities, Anna Lindholm, Pontus Giselsson, International Symposium on Advanced Control of Chemical Processes, Singapore, July 2012. (the continuous model case)