REDUCING REVENUE LOSS DUE TO DISTURBANCES IN UTILITIES USING BUFFER TANKS – A CASE STUDY AT PERSTORP

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Abstract

Utilities, such as steam and cooling water, are often shared by several production areas at an industrial site. In order to minimize the loss of revenue due to disturbances in the supply of utilities, the optimal supply of utilities to different areas has to be determined. It is not evident how utility resources should be divided, as both buffer tank levels, the connections between areas, and the profitability of different products must be considered. This paper presents a case study at Perstorp, the objectives of which were to identify the utilities causing the greatest revenue losses at the site, and suggest strategies for reducing this loss using an on/off modeling approach including buffer tanks between areas.

1. Introduction

In the chemical process industry, companies must continuously improve their operational efficiency and profitability to remain competitive (Bakhrankova (2010)). This means it is of great importance to minimize losses in revenues due to e.g. disturbances in operation. Plant-wide disturbances cause considerable revenue losses at industrial plants (Thornhill et al. (2002); Bauer et al. (2007)). Some of these plant-wide disturbances are caused by utilities, such as steam or cooling water, that are used at most industrial sites. Earlier studies have been performed on the synthesis of utilities to satisfy the demand, for example in Papoulias and Grossmann (1983), Maia et al. (1995) and Maia and Qassim (1997). The study described in this paper focuses on how disturbances in the supply of utilities affect production. A general method for handling disturbances in utilities has recently been proposed by Lindholm et al. (2011b). The method is called the utility disturbance management (UDM) method. In the present study, this framework is applied to an industrial site at Perstorp. The site that is studied produces specialty chemicals and is located in Stenungsund, Sweden. To complete all steps of the general method, a model of the production site is needed. Chemical plants are often complex, and thus difficult and time-consuming to model in detail (Kano and Nakagawa (2008); Niebert and Yovine (1999)). Here, a simple modeling approach is used, in which production areas at a site are modeled as either 'on'

or 'off', i.e. either producing at maximum production rate or not at all. Buffer tanks between areas are also included. If a production area has to be shut down due to a utility disturbance, buffer tanks will allow production to continue for a certain period in downstream areas, before it is necessary to shut down these areas as well. This coarse model will not capture all the variability, but has shown to be useful in providing indications of the effects of disturbances in utilities on production.

The site-model specific steps of the UDM method for on/off modeling including buffer tanks have been described previously (Lindholm (2011)). Here, the method is applied to an industrial site at Perstorp using this modeling approach. The objectives are to obtain an indication of which utilities that cause the greatest revenue losses at the site, and to suggest strategies for reducing these losses. Furthermore, the results obtained when using on/off modeling including buffer tanks are compared with those obtained with on/off modeling without buffer tanks, as reported by Lindholm et al. (2011a). The results of the case study provide insight that could be useful in future studies at the Perstorp site, such as continuous production modeling of the site with respect to utilities. They also provide an indication of which utilities that cause the greatest losses, without having to perform extensive modeling of the site.

Some background that is needed for completing the case study is presented in Sections 2 to 5, and the case study is presented in Section 6.

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2. Utilities and Availability

Utilities are support processes that are utilized in production. Utilities are crucial for plant operation, but are not part of the final product. Examples of common utilities in the process industry are steam, cooling water and electricity. Utilities are often such that they only affect production when their supply is interrupted or does not meet the specifications, i.e. when a utility parameter, such as pressure or temperature, is outside the limits required for normal operation. Utilities are often used plant-wide, and thus disturbances in utilities may affect several production areas simultaneously. From a site-perspective, the problem thus becomes to transfer the variability from critical areas to areas where the variability does less damage (Qin (1998)). In this work, the objective is to divide the resources at a utility disturbance such that the revenue loss caused by the disturbance is minimized. A disturbance in a utility is defined to occur when the measurement of a utility parameter is outside the limits that are set for normal operation of that utility.

The availability of a utility is defined as the fraction of time all utility parameters are inside their normal limits. Area availability is divided into direct and total availability. The direct availability of a production area is defined as the fraction of time all the utilities required in the area are available. The total area availability is obtained when also connections between areas are considered, such that an area is only available if all the required utilities and all upstream areas are available. The measures of utility and area availability are used to estimate the direct and total revenue losses caused by disturbances in utilities.

3. Buffer tanks

Buffer tanks are commonly used to avoid the propagation of disturbances or to allow independent operation of production units (Faanes and Skogestad (2003)). In this study, buffer tanks are located between production areas at a site. These buffer tanks can be seen as both buffer tanks with the purpose to allow independent operation of production areas, and as inventories of products that can be sold on the market.

4. Site modeling

In Lindholm et al. (2011b), three approaches for modeling a site with respect to disturbances in utilities were suggested.

1. **On/off production without buffer tanks**
   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 all its required utilities are available, and does not operate when any of its required utilities are unavailable. It is assumed that there are no buffer tanks between the areas at the site. This means that if an area is unavailable, downstream areas of that area will also be unavailable.

2. **On/off production including buffer tanks**
   The same modeling approach as approach 1, but buffer tanks between areas are included in the model. The buffer tanks act as delays from when an area upstream

of the tank stops producing until its downstream areas have to be shut down.

3. **Continuous production**
   Utility operation and production are considered to be continuous. Areas can operate at any production rate below the maximum limit determined by the operation of utilities.

In this study, on/off modeling including buffer tanks was used.

5. General method for utility disturbance management

A general method for reducing the economic effects of disturbances in utilities was introduced in Lindholm et al. (2011b). The method consists of four steps:

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

The case study at Perstorp presented in this paper focuses on the last two steps of the general method, when using the on/off production modeling approach including buffer tanks. A case study has previously been performed at the same production site using on/off production modeling without including buffer tanks (Lindholm et al. (2011a)). In Section 6.5, the results obtained using on/off modeling with and without buffer tanks are compared.

6. Case study at Perstorp

6.1 Get information on site-structure and utilities

Site Stenungsund is one of 13 sites owned by the enterprise Perstorp. The site consists of 10 production areas. The products of the 10 areas at the site are here denoted product 1-10 for area 1-10 respectively. Internal buffer tanks exist for products 1-5. A flowchart of the product flow at the site is shown in Figure 1. The utilities that are used at site Stenungsund are listed below. Disturbance limits for these utilities have been determined by speaking to operators and other
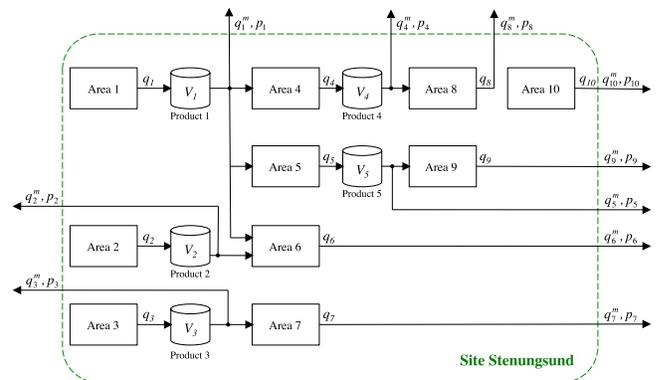

Figure 1.   Product flow at site Stenungsund.

staff at the site and looking into historical databases and log books.

- Steam (High pressure (HP) and middle pressure (MP))
- Cooling water (Cooling water and four cooling fans)
- Electricity
- Water treatment
- Combustion of tail gas (Flare and two combustion devices)
- Nitrogen
- Water (Feed water)
- Compressed air (Instrument air)
- Vacuum system

A table showing which utilities that are needed at each area is shown in Table 1. Here some utilities have been divided into sub-utilities.

Table 1.   Utilities required at areas at site Stenungsund.

	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
Vacuum system	x	x	x	x	x	x	x	x	x	x

The time period August 1, 2007 to July 1, 2010 is considered, and the data has a sampling interval of 1 minute. There has been one planned stop during the time period, from September 15 to October 8, 2009. Data from this time period is not included in the computations.

6.2 Compute utility and area availabilities

Availabilities for all utilities can be computed directly using measurement data and the disturbance limits set in the previous step. In Table 2, the resulting utility availabilities at site Stenungsund for the time period August 1, 2007 to July 1, 2010 are listed.

The direct and total area availabilities for all production areas are computed using utility measurement data, Table 1 and the flowchart of the product flow in Figure 1. The result is given in Table 3.

6.3 Estimate revenue loss due to disturbances in utilities

To estimate the revenue loss due to disturbances in utilities, an estimate of the flows to the market of all products is needed. The flows to the market are assumed to be constant over the time period. The flow to market of a product at maximum production is estimated as the difference of the production of the product and the inflows of the product to

Table 2.   Utility availabilities at site Stenungsund.

Utility	Availability (%)
Flare	100.00
Vacuum system	100.00
Water treatment	100.00
Instrument air	99.98
Cooling fan 7	99.88
Nitrogen	99.87
Electricity	99.28
Feed water	98.91
HP steam	98.55
Cooling fan 1	96.82
Cooling fan 2	96.82
Cooling fan 3	96.82
MP steam	96.76
Combustion device 9	96.06
Combustion device 7	94.18
Cooling water	92.33

Table 3.   Availabilities of areas at site Stenungsund.

Area	Direct availability (%)	Total availability (%)
1	84.45	84.45
2	84.45	84.45
3	84.45	84.45
4	87.24	84.45
5	87.24	84.45
6	87.24	84.45
7	82.37	80.27
8	89.03	83.71
9	83.99	81.46
10	89.60	89.60

downstream areas. If the estimated flow to the market becomes less than zero, it is set to zero and the maximum production of the area(s) downstream is adjusted to correspond the maximum production of the upstream area. The maximum production rates of all products at site Stenungsund are available, but not the corresponding inflows to these areas. The inflows are estimated from the maximum productions in the areas via a conversion factor, denoted y_{ij} for the conversion between product i and j. The conversion factors have been obtained from personnel at the site. An estimation of the flows to the market becomes

$$q_1^m = \max(0, q_1 - q_4 y_{14} - q_5 y_{15} - q_6 y_{16}) \quad (1)$$

$$q_2^m = \max(0, q_2 - q_6 y_{26}) \quad (2)$$

$$q_3^m = \max(0, q_3 - q_7 y_{37}) \quad (3)$$

$$q_4^m = \max(0, q_4 - q_8 y_{48}) \quad (4)$$

$$q_5^m = \max(0, q_5 - q_9 y_{59}) \quad (5)$$

$$q_i^m = q_i, \quad i = 6, 7, 8, 9, 10 \quad (6)$$

where q_i is the maximum production rate of area i in the unit volume/time.

The direct revenue loss, J^{dir}, due to utilities is the loss each utility causes directly, because of reduced production in the areas that require the utility. This loss may be estimated directly from the utility availabilities, the flows to the market, and the contribution margins of the products produced in the areas that require the utility. We get the direct loss

$$J_u^{dir} = (1 - U_u^{av}) t_{tot} \sum_i q_i^m p_i$$

for utility u, when areas i require this utility and U_u^{av} is the availability of utility u. p_i denotes the contribution margin for product i in the unit profit/volume and t_{tot} the total duration of the considered time period. For this case study, there are 1 501 921 sampling points (planned stop not included), which gives a total time of about 25 000 hours of the entire time period.

The total revenue loss due to utilities includes both the direct revenue loss and the indirect revenue loss due to reduced production in areas that are dependent on the areas that require the utility. Here, only downstream effects of disturbances are considered, since a product of an upstream area at the site often can be sold on the market when it cannot be delivered to its downstream area(s). At site Stenungsund, buffer tanks for products 1-5 may thus be utilized to reduce the indirect loss of products 4-9.

For areas with more than one downstream area, a decision must be taken regarding which areas that should be prioritized when the available buffer volume is not enough to provide all areas during the entire disturbance duration. The actual decisions, taken by the operators at the site at the occurrences of the disturbances, are not known for the entire set of measurement data. Also, since the real site does not have on/off production, the areas were not shut down entirely due to small utility disturbances. To get an estimate of the revenue loss for the selected time period, the suggestion is to apply the same decision rule at each disturbance detected in the measurement data. At site Stenungsund, only the buffer tank for product 1 has more than one downstream area. Here, the choice has been made to prioritize downstream areas in order area 5, area 6, area 4, based on profitability measured as profit per time unit for the entire production lines downstream of the buffer tank.

Disturbances in different utilities affect areas at site Stenungsund according to Table 1. Disturbances in utilities that affect an area upstream of a buffer tank, but not all downstream areas of the tank can be handled using the available volume of the buffer tank. At site Stenungsund, the utilities that cause such disturbances are middle pressure (MP) steam, cooling fans in area 1-3 and feed water. Downstream areas might or might not be able to run during the entire failure, depending on the flows that are demanded by these areas, the duration of the disturbance and the level of the buffer tank at the occurrence of the disturbance. For disturbances in MP steam, cooling fans in area 1-3 and feed water, the time t_i that the downstream area i can run during

a failure of the upstream area of duration t_d is given by:

MP steam

$$t_8 = \max\left(0, \min\left(t_d, V_4/q_8^{in}\right)\right) \tag{7}$$

Cooling fan 1

$$t_5 = \max\left(0, \min\left(t_d, V_1/q_5^{in}\right)\right) \tag{8}$$

$$t_6 = \max\left(0, \min\left(t_d, \left(V_1 - t_d q_5^{in}\right)/q_6^{in1}\right)\right) \tag{9}$$

$$t_4 = \max\left(0, \min\left(t_d, \left(V_1 - t_d(q_5^{in} + q_6^{in1})\right)/q_4^{in}\right)\right) \tag{10}$$

Cooling fan 2

$$t_6 = \max\left(0, \min\left(t_d, V_2/q_6^{in2}\right)\right) \tag{11}$$

Cooling fan 3

$$t_7 = \max\left(0, \min\left(t_d, V_3/q_7^{in}\right)\right) \tag{12}$$

Feed water

$$t_{6,1} = \max\left(0, \min\left(t_d, V_1/q_6^{in1}\right)\right) \tag{13}$$

$$t_{6,2} = \max\left(0, \min\left(t_d, V_2/q_6^{in2}\right)\right) \tag{14}$$

$$t_7 = \max\left(0, \min\left(t_d, V_3/q_7^{in}\right)\right) \tag{15}$$

$$t_9 = \max\left(0, \min\left(t_d, V_5/q_9^{in}\right)\right) \tag{16}$$

where V_i is the buffer volume in the buffer tank for product i at the start of the failure, and q_j^{in} the demanded inflow for area j to be able to produce, given by $q_j^{in} = q_j y_{ij}$, as in (1)-(5). For feed water failures that affect area 6, simultaneous failures in area 1 and 2 are taken into account to get t_6.

The indirect revenue loss J_u^{id} due to utility u can then be estimated as

$$J_u^{id} = \sum_{t_d} \sum_i (t_d - t_i) q_i^m p_i$$

for all areas i downstream of buffer tanks, and all disturbance durations t_d for the utility during the entire time period. t_i is the time area i can run during each disturbance, and is given by (7)-(16).

Summarizing both direct revenue losses and indirect losses at buffer tanks we get an estimate of the total loss $J_u^{tot} = J_u^{dir} + J_u^{id}$ due to utility u. In Table 4, utilities are ordered according to the revenue loss they cause, starting with the utility that causes the greatest loss.

6.4 Reduce revenue loss due to future disturbances in utilities

On/off production modeling including buffer tanks gives two strategies for decreasing the revenue loss due to utilities. The first is to choose good stationary buffer tank levels (proactive disturbance management), and the second to control the product flow properly at the occurrence of a disturbance (reactive disturbance management). Below, these two strategies are discussed.

Choice of buffer tank levels Good choices of stationary buffer tank levels can ensure that the site can run even at a failure in one or more areas. In this case study, it has been chosen to only consider downstream effects of a disturbance

Table 4.   Utilities ordered according to the loss they cause.

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	Nitrogen
Cooling fan 3	Cooling fan 3
Cooling fan 2	Cooling fan 2
Instrument air	Instrument air
Cooling fan 7	Cooling fan 7
Flare	Flare
Vacuum system	Vacuum system
Water treatment	Water treatment

upstream of a buffer tank. Thus, only lower constraints on the buffer tank levels will be imposed, and there will be a trade-off between handling as many failures as possible and minimizing inventory at the site. This work does not focus on computing the costs of the inventories to achieve the optimal trade-off between utility disturbance management and cost of inventory. Here, another strategy for choosing the trade-off between these is used, which is described below. Optimal choice of inventory is discussed in e.g. Silver et al. (1998), Newhart et al. (1993) and Hopp et al. (1989).

Choosing the buffer tank levels to handle the longest disturbance durations for utilities will often give unneccesarily high buffer tank levels at normal operation, since disturbances of such long durations often are very uncommon. A suggestion is to choose the levels so that a certain percentage of all disturbances in utilities are handled. In Figure 2, the levels that correspond to handling 90 % of all disturbances in utilities at site Stenungsund are given, based on measurement data from the considered time period. As a comparison, the average buffer tank levels over the considered time period is shown in the figure. It can be seen that the average buffer tank levels over the selected time period are well above the levels required to handle 90 % of all disturbances in utilities. However, the buffer levels are not chosen only to handle disturbances in utilities, but to handle all disturbances at the site and to provide inventory of products to be
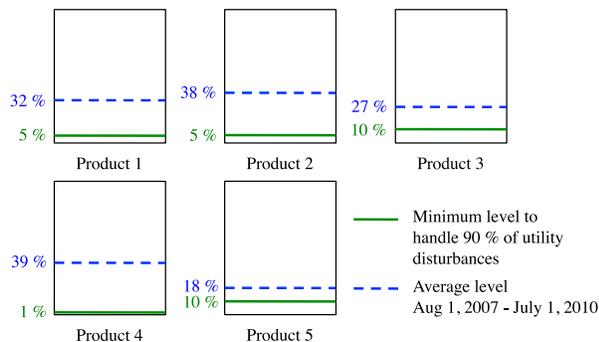
sold to the market. This must be taken into account to evaluate if the buffer tank levels are appropriately chosen. The constraints from disturbances in utilities give one piece that has to be taken into account when choosing desired buffer tank levels.

If upstream disturbances also are taken into account, disturbances that affect a downstream area of a buffer tank, but not all upstream areas, will impose high-level constraints on some buffer tanks.

Control of the product flow   At the occurrence of a disturbance, a decision must be taken on how to control the product flow if the area that suffers a failure has more than one downstream area. A guideline for how to control the product flow when a disturbance occurs is obtained from the simple on/off site model with buffer tanks, where the suggestion is to run the areas according to equations (7)-(16). Since the disturbance duration t_d is not known a priori, t_d is replaced by the estimated disturbance duration t_{est} in the equations. The suggestion in Lindholm (2011) is to let the operators at the site estimate the disturbance duration at the occurrence of a disturbance. This suggestion of the control of the product flow can be recomputed if the estimatie of the disturbance time changes.

Over time, contribution margins for different products could change, which makes it necessary to change the prioritization order of areas. Also, the order can be chosen differently depending on what is the most suitable measure of profitability at the site. Measures that could be used are profit/volume or profit/time.

6.5 Comparison of on/off production modeling with and without buffer tanks

The direct revenue loss caused by disturbances in utilities is the same for on/off production with and without buffer tanks. In Table 5, utilities are ordered according to the estimate of the total revenue loss they cause for on/off production with and without buffer tanks, in descending order.

Table 5.   Utilities ordered according to the total revenue loss they cause.

On/off	On/off with buffer tanks
Cooling water	Cooling water
MP steam	MP Steam
Cooling fan 1	Cooling fan 1
Feed water	Feed water
Combustion device 9	Combustion device 9
Combustion device 7	Combustion device 7
Electricity	Electricity
HP steam	HP steam
Cooling fan 2	Nitrogen
Cooling fan 3	Cooling fan 3
Nitrogen	Cooling fan 2
Instrument air	Instrument air
Cooling fan 7	Cooling fan 7
Flare	Flare
Vacuum system	Vacuum system
Water treatment	Water treatment

Figure 2.   Buffer tank levels at site Stenungsund.

Because of the reduction of the indirect revenue losses caused by MP steam, cooling fans 1-3 and feed water, the ordering is changed when including buffer tanks in the site model. Table 6 shows how much the revenue losses caused by these utilities decrease when internal buffer tanks are utilized. In the table, the utilities are ordered according to the reduction of the revenue loss in money.

Table 6.   Decrease of revenue losses when including buffer tanks.

Utility	Decrease (%)
Cooling fan 1	54
Cooling fan 2	86
Cooling fan 3	80
MP steam	7
Feed water	4

7. Conclusions and Future work

The case study at Perstorp presented in this paper gives ordering of utilities at the site according to an estimate of the loss of revenue they cause, using an on/off modeling approach with buffer tanks between areas. It also illustrates the influence of buffer tanks at the site, by showing how much the loss in revenue caused by disturbances in utilities can be reduced by introducing buffer tanks between the areas.

Strategies for reducing the revenue loss due to utility disturbances are suggested for the Stenungsund site. It should be noted that only disturbances in utilities have been considered. This is only one piece of the entire picture, where also market conditions, cost of inventories and other disturbances must be taken into account. This case study shows which constraints disturbances in utilities place on buffer tank levels and product flow control. The aim of this study was not to achieve the optimal trade-off between utility disturbance management and inventory costs.

The on/off production modeling approach including buffer tanks should give more accurate estimates of the losses that are caused by utilities at a site than the on/off model without buffer tanks. However, areas are still modeled as on or off, and thus the site model does not adequately reflect the actual production. To catch more of the variability, the site should be modeled using a continuous production model. Continuous production modeling of a site is currently being investigated, and will also be applied to Perstorp's site at Stenungsund. With continuous production, more elaborate reactive disturbance management strategies may be obtained, that gives real-time advise to operators on how to control the product flow at the occurrence of a disturbance.

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