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*Published in:*  
[Host publication title missing]

*DOI:*  
[10.2316/P.2011.718-089](https://doi.org/10.2316/P.2011.718-089)

2011

[Link to publication](#)

*Citation for published version (APA):*  
Lindholm, A. (2011). A method for improving plant availability with respect to utilities using buffer tanks. In *[Host publication title missing]* <https://doi.org/10.2316/P.2011.718-089>

*Total number of authors:*  
1

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# **A METHOD FOR IMPROVING PLANT AVAILABILITY WITH RESPECT TO UTILITIES USING BUFFER TANKS**

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## **ABSTRACT**

Disturbances on utilities, such as steam and cooling water, often cause large revenue losses at industrial sites. These disturbances are often hard to handle, since they commonly are plant-wide disturbances that affect more than one production area at the site. Also, the production areas of the site are often dependent on other production areas because of the flow of product through the site, which makes the effect of disturbances on utilities hard to predict. In this paper, a simple method for decreasing the revenue loss due to disturbances on utilities is presented, where production areas are modeled as either operating at full speed or not operating (on/off), and buffer tanks between areas at the site are utilized. Both choice of levels in the buffer tank and control of the product flow at the site during a disturbance are discussed.

## **KEY WORDS**

Disturbance localization, availability, buffer tanks, plant-wide disturbances

## **1 Introduction**

At a production site, utilities such as steam and cooling water are often required for production. Poor operation of these utilities can lead to plant-wide disturbances, which could cause large revenue losses for the site [1]. This motivates the need for methods that minimize the losses due to disturbances on utilities.

A review of the advances in detection and diagnosis of plant-wide disturbances is given in [2]. It is concluded that the work within this field has shown good progress towards the key requirements. However, the topic of how to control the product flow at a site at the occurrence of a plant-wide disturbance is not as extensively studied. An emerging area that touches this subject is enterprise-wide optimization (EWO). The objective of EWO is to reduce the costs and inventories for an enterprise by optimizing the operations of supply, manufacturing and distribution activities [3] [4]. In [5], an approach that integrates and coordinates model predictive controllers (MPCs) is suggested for enterprise optimization. However, constructing the models that are required for MPC is often both hard and time demanding for a large-scale system. The objective in this

work is to provide simple approaches for decreasing the revenue loss due to disturbances on utilities at an industrial site, that do not require large modeling efforts. The method is thereby easy to apply to any site. The core of the method is to utilize buffer tanks between areas to reduce the revenue loss due to disturbances on utilities. One further distinction from EWO is that this work considers the product flow at a site, and not an entire enterprise. This distinction is explained in section 2.

In [6], utility availability is introduced as a measure of the operation of utilities. Utility availability is defined as the fraction of time all utilities operate within certain limits, which define normal operation of the utilities. This is in line with the general availability definition in [7]. What the measure of utility availability does not provide any information of, is how large revenue losses disturbances on a utility cause during the time the utility is not available. For an estimation of this revenue loss, a model of the site must be provided, which specifies the maximum possible production of all areas when one or more utilities are not available. A simple approach is to assume that areas are operating at maximum production speed when all utilities required at the area are available, and not operating when any of the required utilities are not available. An area could also be dependent on the operation of upstream areas, since the product of the upstream area could be a crucial raw material for this area. This is referred to as the on/off approach, and is described more thoroughly in [6]. Using the on/off approach, it is assumed that if an area becomes unavailable, all its downstream areas will at the same time instant also become available. This representation gives a possibility to get a quick view on which losses different utilities at the site cause, but usually substantially overestimates the losses, since no dynamics are included and buffer tanks between areas are not taken into account. In this work, the on/off approach is used, but while taking buffer tanks between areas into account, if such buffer tanks are present at the site. This is still a quick method for estimating the losses due to utilities, but is one step closer to a realistic model of the site. In the method that is suggested here, buffer tanks are used to reduce the effect of disturbances on utilities, both by choosing the optimal level of the buffer tanks and by using the buffer volume optimally during a disturbance. The method is described step by step in sec-

tion 5. The necessary background on site hierarchy, disturbances, availability and buffer tanks is provided in sections 2, 3 and 4.

## 2 Site Hierarchy

In this work, the revenue loss at a site due to disturbances on utilities is investigated. A site consists of one or more production areas, which in turn consist of one or more production units, as defined in [8]. An enterprise can contain one or more sites. At each of these hierarchical levels, a flow chart showing the product flow can be made. An example of flow charts at different levels in the hierarchy is shown in Figure 1. This work belongs at the site/area level in the hierarchy.

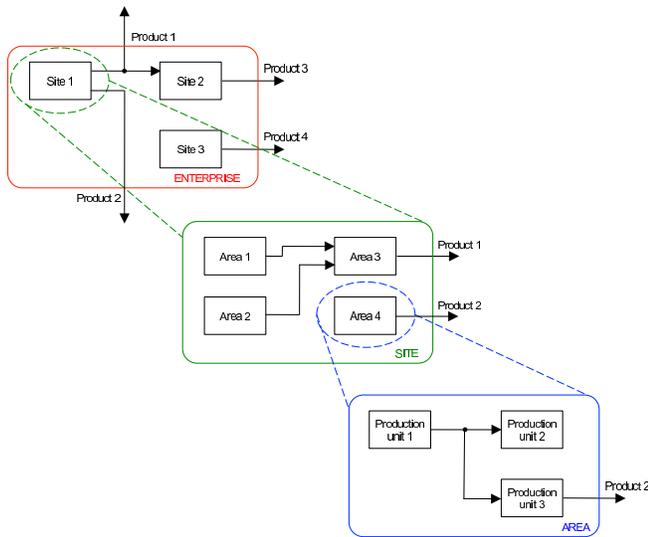


Figure 1. Flowcharts at different levels in the equipment hierarchy.

## 3 Disturbances and Availability

Usually, utilities do not influence the possibility for full production when they operate normally. Normal operation of a utility can be defined as when the certain utility parameters, such as pressure or flow of the utility, are within certain limits. Consequently, a disturbance on a utility can be defined to occur when the measurement of one of these utility parameters goes outside the limits for normal operation [6]. For example, the 41 bar steam net might give the possibility for maximum production when the steam pressure in this steam net is between 33 and 45 bar. Thus, a disturbance on the steam utility is defined as when the steam pressure is below 33 bar or above 45 bar. An example of the operation of the steam utility at an industrial site is shown in Figure 2. Dashed red horizontal lines indicate the critical limits for the utility parameter steam pressure in the figure.

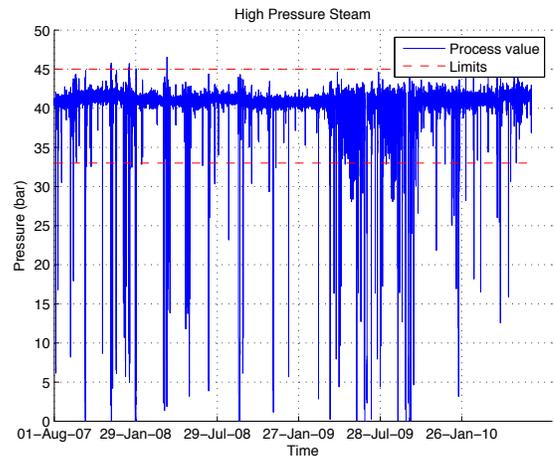


Figure 2. Steam pressure with disturbance limits.

The availability of a utility is calculated as the fraction of time all utility parameters are inside their critical limits. This is an easily obtained estimate that has shown to give a good view of the operation of utilities at industrial sites.

Area availability can also be defined accordingly, as the fraction of time an area operates with respect to utilities.

## 4 Buffer Tanks

Buffer tanks are commonly used to avoid propagation of disturbances or to allow independent operation of production units [9]. In this work, the buffer tanks are not placed between production units (area layer in Figure 1) but between production areas at the site (middle layer in Figure 1). When using the on/off modeling approach for areas, buffer tanks correspond to pure delays from when an area upstream of the buffer tank suffers a disturbance and becomes unavailable, until when areas downstream of the buffer tank become unavailable. In the same manner, the buffer tank acts as a delay from when an area downstream of the buffer tank becomes unavailable until areas upstream of the buffer tank become unavailable. The sole purpose of the buffer tanks in this case is thus to allow independent operation of production areas. An example of areas connected by the product flow through a buffer tank is shown in Figure 3.

In this example the purpose of the buffer tank is to allow area 3, 4 and 5 to operate during a disturbance on area 1, or area 2, or area 1 and 2 simultaneously. The maximum disturbance duration of the disturbances on these areas and the corresponding demanded inflows to area 3, 4 and 5 during the disturbance, gives a lower limit for the buffer tank level. In the same manner, the disturbance duration for disturbances on area 3, 4 and 5 and the corresponding outflows of area 1 and 2 gives an upper limit on the level of the buffer tank. This limit can also be thought of as how much air there must be in the buffer tank for area 1 and

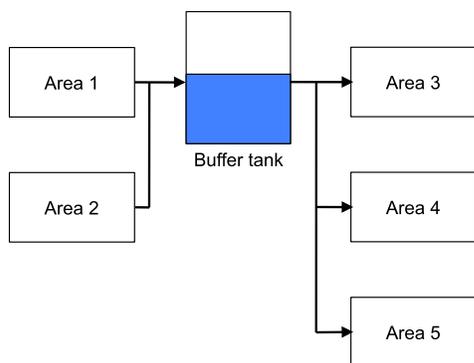


Figure 3. An example of areas connected through a buffer tank.

2 to be able to produce during the entire disturbance on area 3, 4 and 5. Depending on the disturbance durations and flows upstream and downstream, the upper limit on the level might or might not be higher than the lower limit. If the upper limit is higher than the lower limit, the buffer tank is large enough for supplying all areas during the entire disturbance. If not, the buffer tank is not large enough and a revenue loss due to the disturbance is unavoidable. These two situations are illustrated in Figure 4

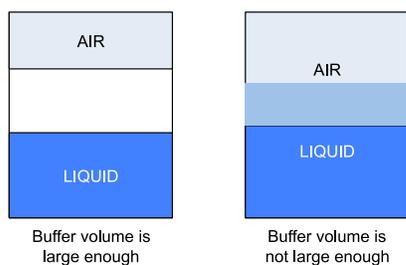


Figure 4. Two scenarios when attempting to choose buffer level.

If the buffer volume is not large enough for supplying all areas during the disturbance, there are two options:

- 1) Choose the optimal level for the current buffer tank
- 2) Replace the buffer tank with a larger tank

For alternative 1), the optimal level depends on the priorities at the site; some areas might be more costly to shut down than other areas, and also, the disturbance duration that was used for computing the level limits might have different probabilities of occurring [10]. With alternative 2), the buffer tank is replaced by a tank that is large enough to ensure that disturbances of durations that are not longer than the durations used for the computation of limits can be handled. However, purchase and installation of new tanks are generally expensive, why this alternative often is not an option at industrial sites.

## 5 A Method for Decreasing the Revenue Loss due to Disturbances on Utilities

A general method for decreasing the revenue loss due to disturbances on utilities, that is independent on the choice of modeling approach, is suggested in [6]. Here, the method is described specifically for the case when on/off modeling is used and buffer tanks between areas are taken into account. The method consists of four steps:

1. Get information on site structure and utilities
2. Compute utility and area availability
3. Compute the revenue loss due to disturbances on utilities
4. Reduce the revenue loss due to future disturbances on utilities

The three steps are described in detail in the following subsections.

### 5.1 Step 1: Get Information on Site Structure and Utilities

Make a flow chart showing the product flow at the site. An example is shown in Figure 5. This flowchart shows the dependence between areas at a certain site.

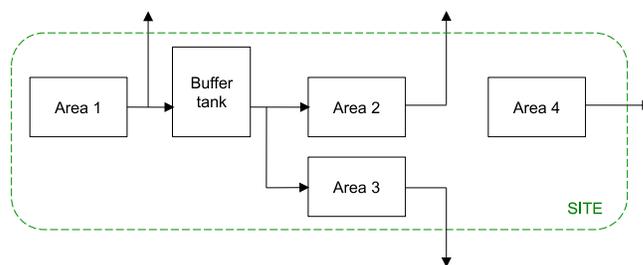


Figure 5. An example of product flow at a site.

List the plant-wide utilities present at the site. Common utilities within the process industry are steam, cooling water, electricity, fuel, water treatment, combustion of tail gas, nitrogen, water, compressed air and vacuum systems. Determine which utilities that are required at each area at the site. This information can be concluded in a table, as in the example in table 1.

Determine the utility parameters that describe the operation of the utilities. Common utility parameters are pressure, flow or temperature of the utilities. For each utility parameter, determine its critical limits, i.e. determine the limits for when the operation of the utilities have negative impact on the production. Get measurement data for the utility parameters for the interesting time period. Also, get information on when planned stops have occurred during the selected time period.

Table 1. Example of a table showing utilities required at each area.

	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	

## 5.2 Step 2: Compute Utility and Area Availability

In this step, the operation of utilities and areas during a certain time period is investigated.

Compute the utility availabilities, i.e. the fraction of time each utility operates correctly, using the disturbance limits set in step 1. Take into account that some utilities are dependent on other utilities to be able to operate. For example, if the feed water utility is not available, steam could not be produced and consequently the steam utility will also be unavailable. If a feed water failure is detected in the measurements, this should not be regarded as a failure of the steam utility as well.

Use the information from step 1 on which utilities that are required at each area to compute the area availability for each area, i.e. the fraction of time each area has access to all required utilities and thereby has the possibility of operating at its maximum production rate. The fraction of time when the areas at the site are not available might give rise to revenue losses, depending on the size and buffer volumes of the buffer tanks between the production areas.

## 5.3 Step 3: Compute the Revenue Loss due to Disturbances on Utilities

In this step, the revenue loss due to disturbances on utilities during a certain time period is computed, if buffer level choices and control of product flow are optimal. This step can be divided into two sub-steps:

- 3 a) Choose buffer tank levels
- 3 b) Control the product flow

First, the optimal levels of the buffer tanks are determined. After the levels have been determined, the effects of disturbances, for which the buffer tanks are not large enough to provide all areas with raw materials during the

entire disturbance duration, have to be considered. The product flow should be controlled so that the revenue loss due to these disturbances is reduced. The two sub-steps are described more thoroughly in the following subsections.

### 5.3.1 Step 3 a): Choose Buffer Tank Levels

The optimal choice of buffer levels can be performed in different ways depending on what is important at the site. If large inventories are not a problem, buffer levels can be chosen to account for the worst-case disturbances, i.e. the disturbance that demands the largest buffer volume. However, having large inventories at normal operation is often costly, why it might be preferable to choose lower buffer tank levels. Regarding estimation of the cost of inventories and optimal choice of inventory or buffer tank levels, much work has been done within operations research, for example in [11] and [12]. At industrial sites, the longest disturbance durations often correspond to disturbances that are very rare. If choosing buffer levels after those worst-case disturbances, the inventory levels will generally be unnecessarily high. One suggestion is to instead choose the level to ensure that a certain percentage of the disturbances, for example 90 % of all disturbances, are handled. This could often decrease the minimum required inventory levels significantly. One way to illustrate how frequent disturbances of different durations are is to make a histogram of stop lengths. An example of such a histogram is shown in Figure 6. In the figure, the buffer delay that ensures that 90 % of all disturbances are handled is indicated with a dashed red vertical line.

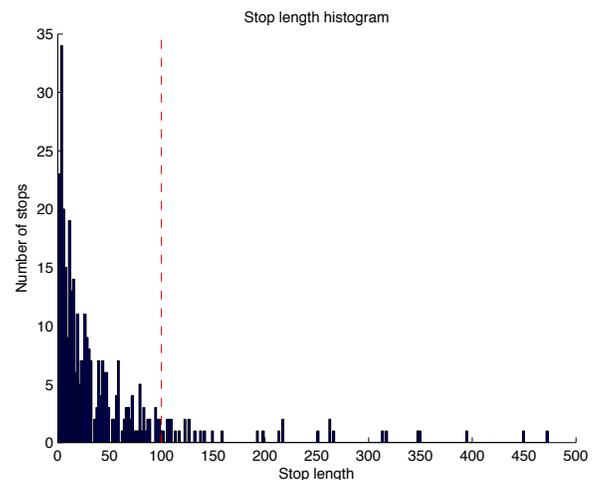


Figure 6. Example of histogram of stop lengths. The bars to the left of the dashed red vertical line correspond to 90 % of the total number of disturbances.

The disturbances that have to be considered for the choice of buffer levels with respect to utilities can be found using the flow chart of the product flow at the site and the table showing which utilities that are required at each area.

Only disturbances that affect any of the upstream areas but not all downstream areas, or vice versa, have to be considered. For example, if considering the site in Figure 5 with the utilities in table 1, we see that a disturbance on the steam utility affects area 1 and area 2 but not area 3. Thus, the level in the buffer tank between area 1 and area 2 and 3 has to be high enough for area 3 to be able to run during a certain time of the steam failure. A cooling water failure, on the other hand, does not give any implications on the choice of level in this buffer tank, since a cooling water failure will affect both area 1, 2 and 3. This originates from the assumption that areas are on or off.

### 5.3.2 Step 3 b): Control the Product Flow

For each disturbance where the buffer volume is not enough for supplying all areas with raw materials during the entire disturbance, there is a choice on how to control the product flow. This could be either when the tank dimensions give a too small buffer volume for handling the specified disturbance durations, or when longer disturbance durations than the durations used for the choice of buffer level occurs. Assuming the on/off approach, this choice can be stated as: Which area or set of areas should be shut down, and when? In which order the areas should be shut down can be determined by considering the profit margin of each product per time unit. The area with the smallest profit margin per time unit should be shut down first.

Thus, start by ordering the products from lowest to highest profitability per time unit. Consider  $N$  areas downstream of a buffer tank. The areas are numbered corresponding to profitability per time unit, so that the product produced in area 1 has the highest profitability per time unit, and area  $N$  has the lowest profitability per time unit. The flow demanded by area  $i$  is  $q_i$  for  $i = 1..N$ . For a disturbance of duration  $t$  upstream of the buffer tank, the optimal control of the product flow is to run area  $i$  downstream for  $t_i$  time units, where  $t_i$  is given by

$$t_i = \max(0, \min(t, \frac{V - t \sum_{k=1}^{i-1} q_k}{q_i})) \quad (1)$$

for areas  $i = 1..N$  downstream of the buffer tank. The notation is shown in Figure 7 for a buffer with one upstream and three downstream areas.

Similarly, for a disturbance of duration  $t$  downstream of the buffer tank, the optimal control of the product flow is to run area  $i$  upstream for  $t_i$  time units, where  $t_i$  is given by

$$t_i = \max(0, \min(t, \frac{V_{tot} - V - t \sum_{k=1}^{i-1} q_k}{q_i})) \quad (2)$$

for areas  $i = 1..N$  downstream of the buffer tank.  $V_{tot}$  is here the total volume of the buffer tank, such that  $V - V_{tot}$  is the non-filled volume of the tank.

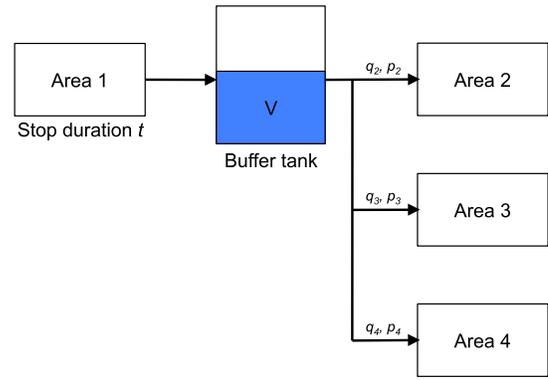


Figure 7. Buffer tank with one upstream and three downstream areas.

The revenue loss  $J$  due to a disturbance upstream or downstream is given by

$$J = \sum_{i=1}^N (t - t_i) q_i p_i \quad (3)$$

where  $p_i$  is the profit margin for the product produced at area  $i$ .

The total revenue loss during the entire time period is obtained by summarizing the losses due to all disturbances at the site, upstream and downstream of all buffer tanks at the site.

### 5.3.3 Step 4: Reduce the Revenue Loss due to Future Disturbances on Utilities

One way to reduce the revenue loss due to disturbances on utilities is to ensure that good buffer tank levels are chosen for all buffer tanks at the site in stationarity. A suggestion is to use the buffer tank levels computed in step 3 a), which are based on previous disturbances on utilities.

Another way to reduce the revenue loss is to improve the control of the product flow at the occurrence of a disturbance. The suggestion is to estimate the duration of a disturbance when it occurs and use the strategy described in step 3 b). The disturbance duration could for example be estimated using knowledge of plant operators, or the duration could be estimated as the most probable disturbance duration. In this paper, start-up costs and times for areas are ignored. However, in reality, these costs are often different for different areas, which could be considered in order to improve the method.

The control of the product flow is determined by inserting the estimated disturbance duration,  $t_{est}$  into (1) and (2) in step 3 b) of the method. The time  $t_i$  that area  $i$  should be run during the disturbance is obtained, under the assumption that the disturbance duration is  $t_{est}$ . These times are thought of as guidelines to the plant operator. If the buffer tank is large enough for the buffer tank to be able to provide all areas during the entire disturbance,  $t_i = t_{est}$

for all  $i$ , and the operator knows that no areas will have to be shut down due to the disturbance, if the disturbance duration does not become longer than  $t_{est}$ . The *estimated* revenue loss is given by (3). The *actual* revenue loss depends on the actual disturbance duration.

If the estimated duration of the disturbance changes, the optimal control of the product flow can be re-computed using the new estimate of the disturbance duration and the current volume in the buffer tank at the time for re-computation.

## 6 Conclusion

This paper presents a quick and simple strategy for reducing the revenue loss due to disturbances on utilities. This is done both by selection of stationary buffer tank levels and by providing guidelines for how to control the product flow at the occurrence of a disturbance.

A strategy for controlling the product flow when a disturbance on a utility occurs is also presented, where the time each area should be run during the disturbance is computed based on the estimated duration of the disturbance. In some cases, the disturbance duration might be hard to estimate, for example if the disturbance is of an unusual character. In those situations, it is probably better to overestimate the duration of the disturbance rather than underestimate it, since an underestimated disturbance duration can result in an empty or full buffer and thereby forced shut down of all areas downstream or upstream of the buffer at the same time instant. Another issue is how to choose which disturbance durations that should be considered when choosing level in the buffer tanks at the site. The best choice depends on the cost of inventory at the site versus the cost of long, and often unusual, disturbances.

## 7 Future Work

An extensive case study, where the method presented in this paper is applied at an industrial site, is currently in progress. This case study will give the company quick solutions for how to reduce the revenue loss due to disturbances on utilities with very little modeling effort. However, if results should be more reliable, and more advanced control of the product flow should be obtained, a more detailed model must be provided. The next step is to develop a dynamic model, where areas could operate at different production speeds depending on the values of all utility parameters. This model would give the possibility to further improve management of disturbances on utilities.

## Acknowledgments

The research is performed within the framework of the Process Industrial Centre at Lund University (PIC-LU) supported by the Swedish Foundation for Strategic Research (SSF).

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