Estimation of Revenue Loss due to Disturbances on Utilities in the Process Industry

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2011

020-0026
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POMS 22nd Annual Conference
Reno, Nevada, U.S.A.
April 29 to May 2, 2011

Abstract

Disturbances on utilities, such as steam and cooling water, often cause large economic losses at industrial sites. Utilities are often shared between production areas, and a disturbance on a utility is therefore likely to affect a large part of the production site. In addition, production areas are often coupled by the product flow at the site. Obtaining a dynamic model of a site, with respect to utilities, is therefore both hard and time-consuming. In this paper, a method for quickly obtaining an estimate of the revenue losses different utilities cause is presented. The method uses a simple modeling approach, where the production areas at the site are modeled as either operating or not operating, i.e. on/off. The strength of this method is that utilities can be ordered according to the revenue loss they cause with very little modeling effort. The method is applied to an industrial site at Perstorp AB.

I. INTRODUCTION

Modeling of large-scale plants is often cumbersome, and the required level of detail of the solution determines the level of detail needed in the model. Developing a detailed model for a complex plant is often too expensive and time-consuming, which motivates the need for simpler models [1]. In [2] the importance of not starting with a too complicated model is emphasized, and it is suggested to start with very simple models and move towards more elaborate models that more closely catches the behavior of the complex system.

In this paper, a simple modeling approach for modeling a site with respect to utilities, such as steam and cooling water, is presented. This modeling approach is used to estimate the revenue losses different utilities cause at the site. The objective is to in the future enrich this model step by step to capture more of the complexity of the system. Some modeling approaches of higher level of detail are suggested in [3]. These approaches are reviewed in section V.

With the simple modeling approach, production areas at the site are assumed to either be operating at maximum speed or not at all, i.e. areas are either on or off. Using this approach, the ordering of utilities according to the revenue loss they cause can quickly be obtained. Measures of utility availability, described in section III, and area availability, described in section IV, are used to estimate the revenue losses due to disturbances on utilities. The procedure is described in detail in section VI and applied to an industrial case in section VII. The case study is performed at Perstorp AB.

II. UTILITIES

Utilities are materials that are required for the operation of a site but are, unlike raw materials, not part of the final product. Below, common utilities in the process industry are listed. For a more thorough description of these utilities and possible disturbances on utilities, see [3] and [4].

- **Steam**
- **Cooling water**
- **Electricity**
- **Fuel**
- **Water treatment utility**
- **Combustion of tail gas**
- **Nitrogen**

- **Water**
- **Compressed air**
- **Vacuum system**

Disturbances on utilities are often plant-wide disturbances, which can have negative impact on both product quality and running costs [5] [6]. This motivates the need for methods for minimizing revenue loss caused by disturbances on utilities.

III. Utility Availability

Utility availability as a measure of the ratio of disturbances on utilities is introduced in [3]. Disturbance limits are set to describe when the site can no longer operate at maximum production rate due to disturbances on utilities, and the fraction of time a utility operates within the disturbance limits is defined as the utility availability. Planned stops should not be included when computing utility availability.

A. Utility dependence

Some utilities are dependent on correct operation of other utilities. For example, if the feed water utility fails, steam could not be produced, and the steam utility will fail as well. This must be taken into account when calculating utility availability; only primary faults on utilities should be considered. The utility dependence can be illustrated as a utility dependence flowchart. An example of such a flowchart is given in figure 1.

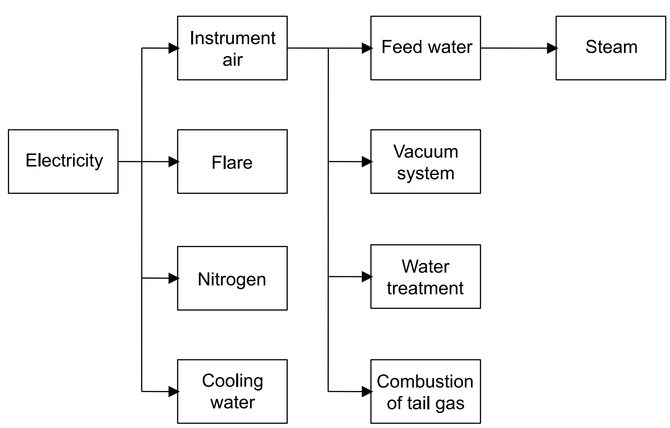

Fig. 1. An example of a utility dependence flowchart.

Utility dependence flowcharts are similar to fault trees, described in for example [7] and [8], but rather than describing the possible root causes of one undesired event, it describes what is affected by a certain fault. For example, the operation of the feed water utility affects the operation of the steam utility. Consequently, if a feed water failure is detected in the measurements, this failure should not be considered a failure of the steam utility as well. In the same manner, if an electricity failure is detected, all other failures should be disregarded during the duration of the electricity failure.

IV. Area Availability

As described in [9], a site consists of one or more production areas. Each area produces one or more products, either end products for external sale or intermediates for further use by other areas at the site. Every area requires a specific set of utilities in order to operate correctly. The set of utilities each area requires can be presented in a table, as in the example in table I.

TABLE I
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	

A simple estimation of the availability of each area, with respect to utilities, is as the fraction of time all utilities needed at the area is available; i.e. the intersection of the concerned utility availabilities. The area availability should be interpreted as the fraction of time the area can operate at maximum production rate, with respect to utilities.

A. Area dependence

One way of using the area availability for modeling an entire site is to assume that if an area is available, it operates at its maximum production rate. If it is not available, it does not produce at all. This will be referred to as the on/off approach. If the on/off approach is used, the flow of product between areas at the site becomes important. An example of a flowchart of the product flow at a site is shown in figure 2. Here it can be seen that area 2 and 3 are dependent on raw materials from area 1, whereas area 4 is independent with respect to the product flow. If the on/off approach is used, this means that if area 1 is unavailable, area 2 and 3 will also be unavailable, because of the lack of raw materials for these areas. This area dependence that arise from the flow of product through the site can be included in the availability computations. For the on/off approach, this means that an area is available when all utilities, and all areas on which the area obtains raw materials from, operate correctly.

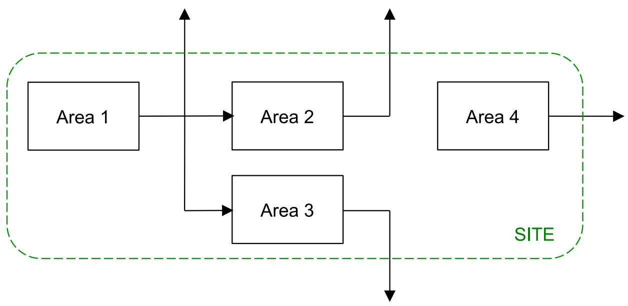

Fig. 2. An example of product flow at a site.

The area availability when including area dependence will be denoted *total area availability* and when not including area dependence, *direct area availability*. Total area availability contains both the direct effects of a utility disturbance, and the indirect effects because of area dependence. By combining the area dependence relations, shown in figure 2 with the table of which utilities that are needed at each area (table I), a table showing direct and indirect effects on areas due to a disturbance on a specific utility can be made. An example that combines the examples in figure 2 and table I is shown in table II.

V. MODELING APPROACHES

In [3] three approaches for modeling a site with respect to utilities are suggested:

1) **On/off modeling without buffer tanks**

Utilities and areas are considered to be either operating or not operating, i.e. on or off. It is assumed that there are no buffer tanks between the areas at the site.

2) **On/off modeling including buffer tanks**

The same modeling approach as in 1), but buffer tanks between areas at the site are also included. A buffer tank acts as a delay from when an area becomes unavailable until areas dependent on the unavailable area also become unavailable.

3) **Dynamic modeling** With dynamic modeling, areas can operate at different rates depending on the set of available utilities and how large the deviations from their ideal operating points are. The objective with dynamic modeling is to minimize the revenue loss by transferring the variability of the utility parameters from sensitive locations to a location where it does less damage [10] [11].

TABLE II

EXAMPLE OF DIRECT AND INDIRECT EFFECT ON AREAS DUE TO DISTURBANCES ON UTILITIES.

	Area (direct effect)	Area (indirect effect)
Steam	1, 2	3
Cooling water	1-4	–
Electricity	1-4	–
Fuel	1	2, 3
Water treatment utility	2, 4	–
Combustion of tail gas	1, 2	3
Nitrogen	1-4	–
Water	1-4	–
Compressed air	1-4	–
Vacuum system	1-3	–

The level of detail of the selected modeling approach determines the level of detail of the strategies that could be developed for minimizing the loss.

In this paper, modeling approach 1), on/off modeling without buffer tanks, is described. With this approach, a quick answer of which utilities that causes the largest losses at a site is obtained. The total revenue loss caused by utilities can often be significantly decreased if the availability of the utility that gives the largest loss can be increased. The knowledge acquired during the development of the on/off modeling method should also be useful when moving towards more advanced modeling strategies.

VI. ON/OFF MODELING WITHOUT BUFFER TANKS

Using the on/off modeling approach, utilities can be ordered according to the revenue loss they cause by performing the following three steps:

1) Get information on site-structure and utilities
2) Compute utility and area availability
3) Compute revenue loss due to disturbances on utilities

A. Step 1: Get information on site-structure and utilities

Draw the overall structure of the site by highlighting its production areas and the physical connections between them. The structure could be represented by a flowchart, as in figure 2.

List the plant-wide utilities present at the site. Common utilities within the process industry are listed in section II. Consider the hierarchy of the utilities; the utility dependence. Draw a utility dependence flowchart, see the example in figure 1. Also, make a table of which utilities that are required at each area, as in the example in table I.

Determine the utility parameters and their critical limits for all utilities, i.e. determine the limits for when disturbances in the utility parameters have negative impact on the production. Utility parameters are commonly chosen as temperature, pressure or flow of the utility. As an example, production might be affected if the steam pressure is lower than 41 bar in a 43 bar steam net, or if the cooling water temperature is higher than 27 °C. Get measurement data for the utility parameters for the interesting time-period and list all planned stops during this period.

B. Step 2: Compute utility and area availability

Compute the utility availabilities, i.e. the fraction of time each utility operates correctly, using the disturbance limits set in step 1. Take utility dependence into account when computing the utility availabilities. Computation of utility availability is discussed further in section III.

Compute the area availability for each area, i.e. the fraction of time each area has access to all required utilities and has the possibility of operating at its maximum production rate. Do the computations both including and not including area dependence. Further information about area availability is given in section IV.

C. Step 3: Compute production loss and revenue loss

Determine the maximum production rates of each product.

Use on/off modeling, i.e. assume that an area operates at its maximum production rate when available, and does not produce at all when unavailable. Use the area availability to compute the production loss of each product due to all disturbances on utilities. Do the computations both including, and not including area dependence because of the product flow. Translate the production losses into revenue losses using the profit margins for each product.

Use the utility availabilities to calculate an estimate of how large production loss each utility causes. Do the computations both including, and not including area dependence. Translate the production losses into revenue losses.

VII. CASE STUDY AT PERSTORP AB

A case study is performed at Perstorp AB, at their site in Stenungsund, Sweden, to illustrate the use of the on/off modeling method described in section VI.

A. Step 1: Get information on site-structure and utilities

Site Stenungsund is one of 13 sites owned by the enterprise Perstorp AB. The site consists of 10 production areas. For definition of enterprise, site and area, see [9]. The products of the 10 areas at the site are here denoted product 1-10 for area 1-10 respectively.

A flowchart of the product flow is shown in figure 3.

Site Stenungsund has all utilities listed in section II. There are two steam nets at the site, one with high pressure steam, ideally 41 bar, and one with middle pressure steam, ideally 14 bar.

Four areas, area 1, 2, 3 and 7, have cooling fans that cool local cooling coils, in addition to ordinary cooling water.

Site Stenungsund uses both 130 kV and 40 kV electricity. A list of disturbances on electricity is provided by the supplier.

Fuel is not included as a utility in this case study. However, the effects of fuel being unavailable will show up in measurements of other utilities, for example steam.

For the water treatment utility (WTU), there are monthly limits for how large amounts of suspended material (SUSP) and dissolved organic carbon (DOC) that are allowed in the outgoing water that should

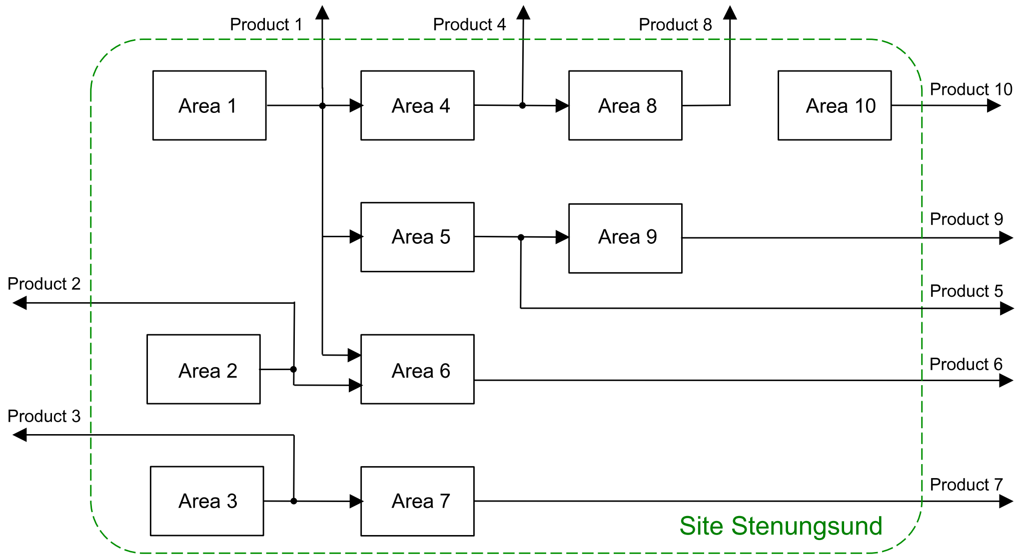

Fig. 3. Flowchart of the product flow at site Stenungsund.

not be exceeded. There are also more strict limits for how much of these substances that are allowed in the outgoing water each year. If the yearly limits are exceeded, the site has to be shut down immediately. The monthly and yearly limits are individual for each production site. In this case study, only the yearly limits are considered.

The site contains a flare and there are also three areas, area 7, 8 and 9, that have devices for local combustion of tail gas at normal operation. However, measurements are only available for the combustion devices at area 7 and area 9.

Nitrogen is used to maintain pressure in vessels.

Both feed water, washing water and fire protection water is used at the site, but only feed water will be considered in this case study.

Compressed air could be both process air and instrument air. At site Stenungsund only instrument air is used.

The vacuum systems are individual for each area.

The utility dependence is given by the utility dependence flowchart in figure 1 in section III-A.

A table showing which utilities that are required at each area is shown in table III.

Table IV shows the direct and indirect effects of disturbances on utilities at site Stenungsund.

Disturbance limits for disturbances on utilities at site Stenungsund have been set with help from personnel at the site. These limits are listed below.

- **Steam**
  - Pressure in high pressure steam net below 33 bar or over 45 bar
  - Pressure in middle pressure steam net below 12 bar
- **Cooling water**
  - Cooling water temperature higher than 27°C
  - Temperature of water cooled by cooling fan in area 1, 2 or 3 higher than 70°
  - Temperature of water cooled by cooling fan in area 7 higher than 65°
  - Loss of cooling water flow
- **Electricity**
  - Voltage below 99% of normal voltage for 40 kV or 130 kV electricity
  - Loss of low voltage electricity
  - Loss of electricity
- **Water treatment utility**
  - Amount of SUSP or DOC in outgoing water more than 4000 kg a year
- **Combustion of tail gas**
  - Flare flame goes out
  - Failure of combustion device at area 7 or 9
- **Nitrogen**
  - Pressure in main nitrogen pipe less than 21 bar
- **Water**
  - Pressure in main feed water pipe less than 20 bar
- **Compressed air**
  - Zero pressure of instrument air
- **Vacuum system**
  - Loss of vacuum system.

Measurement data for all utility parameters is available.

TABLE III
UTILITIES NEEDED 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 fans	x	x	x				x			
Electricity	x	x	x	x	x	x	x	x	x	x
WTU	x	x	x	x	x	x		x	x	
Flare	x	x	x	x	x	x				x
Combustion devices							x	x	x	
Nitrogen	x	x	x	x	x	x	x	x	x	x
Feed water	x	x	x	x	x			x		
Compressed air	x	x	x	x	x	x	x	x	x	x
Vacuum system	x	x	x	x	x	x	x	x	x	x

B. Step 2: Compute utility and area availability

Since all needed measurements are available at site Stenungsund, the availabilities of all utilities can easily be computed from historical measurement data. In this case, data from August 1, 2007 to July 1, 2010 has been used. Planned stops and simultaneous faults for dependent utilities are not included in the computations. Some utilities have been divided into its sub-utilities to give a more specific view of what causes the largest revenue losses; the steam utility has been divided into high pressure (HP) steam and middle pressure (MP) steam, the cooling water utility into cooling water and cooling fans and combustion of tail gas into flare and devices for combustion of tail gas at normal operation (here denoted ”combustion devices”). In table V the resulting utility availabilities at site Stenungsund during the time period August 1, 2007 to July 1, 2010 are listed.

Using table III, the area availability for all production areas at site Stenungsund can be computed. The computations are performed both including area dependence (total availability) and not including area dependence (direct availability). The resulting area availabilities are listed in table VI.

TABLE IV

DIRECT AND INDIRECT EFFECT ON AREAS AT SITE STENUNGSUND DUE TO DISTURBANCES ON UTILITIES.

	Area (direct effect)	Area (indirect effect)
HP steam	7-10	–
MP steam	1-7, 9	8
Cooling water	1-10	–
Cooling fan, area 1	1	4-6, 8, 9
Cooling fan, area 2	2	6
Cooling fan, area 3	3	7
Cooling fan, area 7	7	–
Electricity	1-10	–
Water treatment utility	1-6, 8, 9	7
Flare	1-6, 10	7-9
Combustion device, area 7	7	–
Combustion device, area 9	9	–
Nitrogen	1-10	–
Feed water	1-5, 8	6, 7, 9
Compressed air	1-10	–
Vacuum system, area 1	1	4-9
Vacuum system, area 2	2	4-9
Vacuum system, area 3	3	4-9
Vacuum system, area 4	4	8
Vacuum system, area 5	5	9
Vacuum system, area 6	6	–
Vacuum system, area 7	7	–
Vacuum system, area 8	8	–
Vacuum system, area 9	9	–
Vacuum system, area 10	10	–

C. Step 3: Compute production loss and revenue loss

The maximum production rates of all products at site Stenungsund are available but are not shown here due to secrecy matters.

Using the computed area availabilities in table VI and the maximum production rates, an estimation of the production loss of each product due to disturbances on all utilities is calculated. The production losses are translated into revenue losses via the profit margins. The three products and areas that showed to give the largest direct and total revenue losses are listed below, starting with the product that stands for the largest loss.

TABLE V

UTILITY AVAILABILITIES AT SITE STENUNGSUND.

Utility	**Availability** (%)
Water treatment utility	100.00 %
Flare	100.00 %
Vacuum systems	100.00 %
Electricity	99.98 %
Compressed air	99.98 %
Cooling fan, area 7	99.88 %
Nitrogen	99.87 %
Feed water	98.99 %
Steam HP	98.53 %
Cooling fan, area 1	96.78 %
Cooling fan, area 2	96.78 %
Cooling fan, area 3	96.78 %
Steam MP	96.74 %
Combustion device, area 9	96.09 %
Combustion device, area 7	94.19 %
Cooling water	92.26 %

Direct revenue loss:

1) Product 1
2) Product 9
3) Product 3

Total revenue loss:

1) Product 9
2) Product 1
3) Product 6

Using table IV and the computed utility availabilities in table V, the production loss due to disturbances on each utility is estimated. The production losses are translated to revenue losses via the profit margins. The three utilities that cause the largest direct and total revenue losses are listed below, starting with the utility giving the largest loss.

TABLE VI

AVAILABILITIES OF AREAS AT SITE STENUNGSUND.

Area	**Direct availability** (%)	**Total availability** (%)
1	85.14	85.14
2	85.14	85.14
3	85.14	85.14
4	87.95	85.14
5	87.95	85.14
6	87.96	85.14
7	83.01	80.91
8	89.74	84.39
9	84.64	82.08
10	90.39	90.39

Direct revenue loss:

1) Cooling water
2) Steam
3) Combustion of tail gas

Total revenue loss:

1) Cooling water
2) Steam
3) Combustion of tail gas

D. Results

With the on/off modeling approach, ordering of utilities according to the revenue loss they cause at site Stenungsund is achieved. The utility that gives rise to the largest revenue loss at the site is the cooling water utility, assuming that all disturbance limits are correctly set. Choosing the disturbance limits is an iterative procedure; if the result does not seem to agree with the actual production losses at the site, the disturbance limits might have to be reviewed.

Another result that might be interesting is which product, or which area, that corresponds to the largest revenue loss due to disturbances on all utilities. In the ranking of areas in step 3 of the method, section VII-C, it can be seen that product 1, produced in area 1, stands for the largest direct revenue loss due to utilities at site Stenungsund during August 1, 2007 to July 1, 2010. Product 9, produced in area 9, stands for the largest total revenue loss during the same time-period.

The answer to question B), stated in section V, is that we should try to improve the availability of the cooling water utility to reduce the revenue loss due to utility disturbances.

VIII. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper, a quick method for ordering utilities according to the revenue loss they cause is presented. The areas that stand for the largest revenue losses could also be determined.

The method uses computation of availability for both utilities and areas. Direct availability, including only utility failures, and total availability, where also lack of raw materials is considered, is introduced. In the total availability computations, it is assumed that downstream areas are affected of the operation of upstream areas. However, upstream areas might also be affected by the operation of downstream areas, since the upstream area might have no place to deliver its product to if the downstream area is not available. The reason for the assumption that upstream areas affect downstream areas and not vice versa is that the product from each area often can be stored in buffer tanks or delivered directly to a customer if a downstream area is not available.

An interesting result is that it can not be concluded from the product flow which area that has the lowest total availability. What can be concluded is that the area located furthest downstream never can have a higher total availability than its upstream areas if using the on/off modeling method. However, an area with fewer upstream areas might still have a lower total availability than an area with more upstream areas, as is the case with area 7 in the case study. The total area availability depends entirely on the combination of utilities the area, and its upstream areas, requires. Thus, it is possible that the area that has the lowest direct area availability is not the area with the lowest total availability. In the case study, it can also be seen that the product that stands for the largest direct revenue loss does not stand for the largest total revenue loss. Furthermore, neither of these products is produced in area 7, which is the area with the lowest both direct and total area availability. This shows that availability, production rate and profit margin for each area are all important to take into account.

When having used the method to obtain the answer of which utilities that give rise to the largest revenue losses, the objective is to improve the availabilities of these utilities. After a time period where adjustments have been made (for example in terms of maintenance or acquisition of additional equipment) in order to improve the availabilities, the method can be applied to the site again. The obtained result will show if the adjustments have had any effect on the revenue losses due to the different utilities. If other utilities now stand for the largest revenue losses, this should be the next utility to focus on at the site.

B. Future works

To develop strategies for minimizing the revenue loss due to disturbances on utilities, a more advanced modeling method than the on/off modeling method presented in this paper has to be used. However, the on/off modeling method gives a quick indication of the utilities and locations that stand for the largest revenue losses at the site, which might be useful for situations where time and modeling effort are critical parameters. The development of more advanced modeling methods is currently investigated.

C. 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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