A Tool for Utility Disturbance Management

Lindholm, Anna; Johnsson, Charlotta

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A Tool for Utility Disturbance Management

Anna Lindholm * **Charlotta Johnsson** *

* *Department of Automatic Control, Lund University, Sweden (e-mail: anna.lindholm@control.lth.se).*

Abstract: Disturbances in the supply of utilities may lead to large economical losses at industrial sites. In order to take appropriate decisions on for which utilities improvement efforts should be made, a tool for evaluating the economical effects of utility disturbances is needed. This paper presents a tool for quickly estimating the revenue loss caused by each utility, using simple matrix operations. A matrix representation of a site is introduced to be able to quickly get key performance indicators for any site. The revenue loss is estimated using an on/off production modeling approach.

Keywords: Disturbance management, Performance evaluation, Enterprise modeling, Utilities, Process control, Decision support systems, Data processing

1. INTRODUCTION

Process industrial sites are often complex, and modeling such sites in detail is often both hard and time-consuming (Niebert and Yovine (1999)). In situations where quick decisions must be taken, there is often not time for detailed modeling. For such situations, key performance indicators (KPIs) can be used for decision support, for example at decisions on where to focus maintenance efforts or include more redundancy. One decision support framework that utilizes KPIs for disruption management in the supply chain is presented in Bansal et al. (2005).

In this study, the focus is on disturbances in utilities, such as steam and cooling water. These disturbances are often plant-wide disturbances that affect several production areas at a site, which makes their impact on production hard to predict. Lindholm et al. (2011b) presented a general method for reducing the economical effects of disturbances in utilities. This method was applied to an industrial site in Lindholm et al. (2011a) using an on/off production modeling approach. In the present study, a matrix representation of a site and its utilities is introduced, that simplifies use of the method in Lindholm et al. (2011b). Performace indicators such as utility and area availability are easily calculated, and the revenue loss caused by each utility is estimated via the on/off production modeling approach. A general tool for proactive disturbance management is presented, that can efficiently be applied to any process industrial site, since it utilizes the general matrix representation. The case study in Lindholm et al. (2011a) is redone using this new utility disturbance management tool, to show the usefulness of the representation framework.

2. PHYSICAL HIERARCHY OF AN ENTERPRISE

According to the role based equipment hierarchy defined in the standard ISA-95.00.01 (2009), an enterprise contains one or more sites, which in turn consist of one or more areas. Each production area has one or more production units and each production unit consists of one or more units.

The enterprise determines which products to manufacture and at which site they should be produced. Sites are usually geographically grouped, and are used for rough-cut planning and scheduling. Areas are usually grouped by their geographic location and by their products. Each area produces one or more products, either end products for external sale or intermediates for further use by other areas at the site. Production units generally include all equipment required for a segment of continuous production. A production unit in the process industry could be e.g. a reactor or a distillation column. Units are composed of lower level equipment, such as sensors and actuators.

For application of a general disturbance management method, a conveninent way of representing a site is needed. Usually, a flowchart is available at a site, that depicts the areas of the site and the product flow through these areas. Using the flowchart, a matrix representation of the site can easily be produced. How this is done is discussed in Section 7.

3. UTILITIES

Utilities are support processes that are utilized in production, but are not part of the final product. Utilities may be seen as belonging to the 'Material' category in the standard ISA-95.00.01 (2009). Common utilities within the process industry are e.g. steam, cooling water and electricity. For a more complete list, see e.g. Brennan (1998) or Lindholm et al. (2011b).

Utilities are often such that they only affect production when their supply is interrupted or does not meet the specifications. In Lindholm et al. (2011b), disturbances in the supply of utilities are defined as when the measurement of a utility parameter, such as temperature or pressure, goes outside a limit at which the poor operation of the utility will have negative consequences for the production at the site. One utility may be affected by several utility parameters, for example both flow and temperature of the utility. The disturbance limits may be set using knowledge of personnel at a site or may be estimated using measurement data.

4. DISTURBANCE MANAGEMENT

Two main approaches of disturbance management could be identified, disturbance handling at the occurrence of a disturbance, and preventive disturbance management strategies that aim to reduce the number of disturbances. These two approaches have been given different names within different research areas, and are sometimes also divided into sub-approaches. Here the terms *reactive* and *proactive* disturbance management are used. These terms are also used in Barroso et al. (2010), where they are defined for the supply chain, and in Monostori et al. (1998), where they are used in the context of scheduling. The formal definitions of reactive and proactive disturbance management that are used in this paper are given below.

> *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.

The tool that is introduced in this paper can be used for proactive disturbance management.

5. PERFORMANCE INDICATORS

5.1 Utility Availability

The availability of a production unit is according to the standard ISO/WD-22400-2 (2011) the ratio between the actual production time and the planned allocation time, where the planned allocation time is the time in which the unit can be used (the operation time) minus the planned downtime. For utilities, availability is defined in Lindholm et al. (2011b) as the fraction of time all utility parameters are inside their limits. This represents the fraction of time when there is a possibility for maximum production, assuming that all utility disturbance limits have been correctly set. This means that a utility is available when all its utility parameters are inside their limits, and not available otherwise. Utility availability can be computed if measurements of all utility parameters are available. Planned stops should not be included in the availability computations. Calculation of utility availabilities using a matrix representation of a site and its utilities is handled in Section 7.2.

Utility dependence Some utilities are dependent on other utilities, which may have as consequence that a disturbance in one utility also shows up in the measurements of other utilities. For example, if feed water is not available, steam could not be produced, and the steam utility could not possibly be available. This should be considered a feed water failure and not a steam failure, since feed water is the root cause of the disturbance. Utility dependence can be represented in a flowchart. An example of a utility dependence flowchart is given in the example in Section 8.

Utility dependence can be taken into account when calculating utility availability. If it is not taken into account, the utilities dependent on other utilities will appear to have lower availability than they actually have. Calculation of utility availability when taking utility dependence into account is handled in Section 7.2.

In some cases, interdependency between utilities might occur. An example is the reliance of water distribution on electricity, and simultaneous reliance of electricity generation on water. This would appear as loops in the utility dependence flowchart. The computational framework presented in Section 7.2 can currently not handle this. The reason is that the root cause of the disturbance has to be determined, which is impossible if only considering one sample point in utility measurement data. One solution to the problem is to, if possible, divide the considered utilities into sub-utilities to get rid of the loops in the utility dependence flowchart. Another solution is to consider the order in which the failures show up in measurement data to determine the root cause of each disturbance.

5.2 Area Availability

A simple estimate of the availability of each area, with respect to utilities, is the fraction of time all utilities needed at the area are available; i.e. the intersection of the operation of all concerned utilities. The measure of area availability should be interpreted as the fraction of time an area has the possibility of operating at maximum production rate, with respect to utilities. Area availability computed without considering the connection of areas at a site is denoted *direct area availability.*

Area dependence If an area is unavailable, this may also affect other areas at the site, since areas could be dependent on obtaining raw materials from, or delivering product to, other areas. The area interdependence can be seen in a flowchart of the product flow at the site.

To include area dependence in the measure of area availability, *total area availability* is introduced. Total area availability is defined as the fraction of time all the required utilities, and all areas that the area is dependent on, are available. Thus, total area availability contains both the direct effects of a utility disturbance, and the indirect effects because of area dependence. Computation of both direct and total area availability using matrices is handled in Section 7.3.

5.3 Production Revenue Loss

Production revenue loss is obtained when an area cannot operate at the desired production rate. The revenue loss is here defined as the contribution margin multiplied by the duration when production was reduced, and by the difference of the desired production rate and the actual production rate during the time period. The contribution margin is the marginal profit per volume.

Here, maximum production is considered to be the desired production rate, since this is how the utility disturbance limits are defined. The flows to the market of the products of the site at maximum (steady-state) production are used to estimate the revenue loss. For an area, the direct revenue loss is the loss of revenue due to poor operation of the utilities at that area. The total revenue loss is obtained if also the effects of utility disturbances in areas that the area is dependent on are considered. For utilities, the direct revenue loss is the loss each utility causes directly, because of reduced production in the areas that require the utility. The total revenue loss also includes the revenue loss due to reduced production in areas that are dependent on the areas that require the utility.

An estimate of the production revenue loss due to disturbances in utilities can quickly be obtained using an on/off production model of the site. The computations may be performed with matrices, as described in Section 7. On/off production modeling is described in Section 6. If the desired production rate varies during the time period that is considered, the period may be divided into intervals for which the desired production rate is constant. An estimate of the revenue loss for the entire time period is then obtained by summarizing the partial estimates.

6. ESTIMATION OF REVENUE LOSS

6.1 On/Off Production Modeling

The on/off production model is the simplest way of modeling the effect of utility disturbances on production. With this modeling approach, 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 is unavailable. It is assumed that there are no buffer tanks between the areas at the site. This means that if an area is unavailable, the areas downstream with respect to the product flow will also be unavailable. The on/off model does not adequately reflect how the actual production is managed for most sites, but is because of its simplicity useful for obtaining quick estimates of production losses due to disturbances. The estimates can be used to help identifying which disturbances that have the greatest economical effects.

6.2 Estimation of Revenue Loss using On/Off Modeling

Estimation of Revenue Loss for each Product With on/off production modeling without buffer tanks, areas are assumed to be operating at maximum production speed when available, and not at all when not available. Thus, the direct and total area availabilities may be used to estimate the direct and total revenue loss for each product due to all disturbances in utilities. The area availabilities and the flows to the market at maximum production are used to compute the production losses, which are translated into revenue losses using the contribution margins of the products. The computations can be done efficiently with matrices, see Section 7.4.

Estimation of Revenue Loss due to each Utility For on/off production modeling without buffer tanks, the utility availabilities may be used to estimate the direct and total revenue loss caused by each utility. The utility availabilities and the flows to market at maximum production are used to compute the direct production losses, which are translated into revenue losses using the contribution margins. For the computation of the total revenue losses due to each utility, information on the connection of areas and which utilities that are required at each area is also needed. The computations can be done efficiently with matrices, see Section 7.5.

7. MATRIX REPRESENTATION AND COMPUTATIONS

7.1 Representation

Site Structure As described in Section 2, a site consists of one or more production areas. Some areas produce intermediate products that are refined to end products in other areas, so that the product of an area is the raw material to one or more other areas. This gives interdependence of areas that can be described by an area dependence matrix, where a one at row i and column j means that area i obtains raw material from area j. A zero means that the areas are independent. Areas that are dependent on each other (a loop/recycle in the production flowchart) will have a one both at row i, column j, and at row j, column i. All areas are assumed to be dependent on themselves, which gives ones on the diagonal of the matrix. The area dependence matrix, A_d, will be of size $n_a \times n_a$, where n_a is the number of areas at the site.

Additional information about the site that is required in order to complete all calculations of this section is the flows to the market of all products at maximum production, q^m, and the contribution margins of all products, p. Both q^m and p are column vectors, with the elements ordered in the same order as the areas in the area dependence matrix.

Utility Measurement Data Measurement data of utility parameters can be compared to the critical limits for each utility to form arrays where, for each sample, the value is one if the utility works properly, and zero otherwise. These arrays could be row-stacked to obtain the utility operation matrix, U of size $n_u \times n_s$, where n_u is the number of utilities, and n_s the number of samples. The sampling interval is denoted t_s.

Utility Requirements Every production area requires a specific set of utilities in order to operate correctly. The set of utilities each area requires can be presented in a area-utility matrix, where a one at row i and column j means that area i requires utility j. A zero means that area i does not require utility j. This matrix is denoted A_u and has n_a rows and n_u columns.

7.2 Utility Availability

Using the utility operation matrix, U, the utility availabilities are obtained as a column vector, U_{av}, by taking the row-sum of the utility matrix and dividing by the number of samples, or equivalently

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

where $\mathbf{1}$ denotes a column vector of ones.

Utility Dependence In Section 5.1, utility dependence was represented by a flowchart showing the interdependence of utilities. Utility dependence can also be represented in a matrix, U_d, where a one at row i, column j means that utility i is dependent on the operation of utility j. A zero means that the utilities operate independently of each other. All utilities are assumed to be dependent on the operation of themselves, which gives ones on the diagonal of the matrix. If utility dependence is considered, the utility operation matrix becomes

$$U_{ud} = \text{sign}\left(U + \text{sign}\left((I - U_d)(U - \mathbf{1}\mathbf{1}^T)\right)\right) \quad (2)$$

where $\mathbf{1}$ denotes a column vector of ones, and I is the identity matrix.

7.3 Area Availability

A column vector containing the direct area availabilities of all areas at a site, A_{av}^{dir}, is obtained by

$$A_{av}^{dir} = A_{dir} \cdot \mathbf{1}/n_s \quad (3)$$

where

$$A_{dir} = \mathbf{1}\mathbf{1}^T + \text{sign}\left(A_u(U - \mathbf{1}\mathbf{1}^T)\right) \quad (4)$$

A_{dir} is denoted the direct area operation matrix. Note that the utility operation matrix without consideration to utility dependence should be used, since the measure of area availability should describe how the areas actually have operated during a time-period.

The total area availabilities of all areas are given by the column vector A_{av}^{tot}, which is computed as

$$A_{av}^{tot} = A_{tot} \cdot \mathbf{1}/n_s \quad (5)$$

where

$$A_{tot} = \mathbf{1}\mathbf{1}^T + \text{sign}\left(A_d(A_{dir} - \mathbf{1}\mathbf{1}^T)\right) \quad (6)$$

A_{tot} is denoted the total area operation matrix.

7.4 Estimation of Revenue Loss for each Product

When on/off production modeling without buffer tanks is used, the estimation of the revenue loss for each product can be computed directly using (3) and (5). The direct revenue losses become

$$J_p^{dir} = \left(\mathbf{1} - A_{av}^{dir}\right) .* q^m .* p n_s t_s \quad (7)$$

and the total revenue losses

$$J_p^{tot} = \left(\mathbf{1} - A_{av}^{tot}\right) .* q^m .* p n_s t_s \quad (8)$$

where '.∗' denotes the entry-wise product. Direct and total losses for products are defined in Section 5.3.

7.5 Estimation of Revenue Loss due to each Utility

With on/off production modeling without buffer tanks, the direct and total revenue loss due to each utility (J_u^{dir} and J_u^{tot}) are obtained using the utility availabilities, with utility dependence taken into consideration ((1) and (2)):

$$J_u^{dir} = \text{diag}\left[\mathbf{1} - U_{av}^{ud}\right] \cdot A_u^T (q^m .* p) n_s t_s \quad (9)$$
$$J_u^{tot} = \text{diag}\left[\mathbf{1} - U_{av}^{ud}\right] \cdot \text{sign}\left(A_d A_u\right)^T (q^m .* p) n_s t_s \quad (10)$$

where '.∗' denotes the entry-wise product. Direct and total losses due to utilities are defined in Section 5.3.

8. AN EXAMPLE

In this section, an example is given that illustrates the representation and computations defined in Section 7.

8.1 Representation

Site Structure A flowchart of the product flow at a site is shown in Fig. 1. 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.

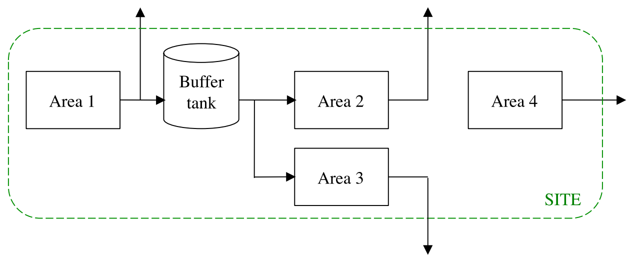

Fig. 1. Product flow at the site in the example.

This gives the area dependence matrix

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

If the maximum production rates of the areas are $q_1 = 4$, $q_2 = 2$, $q_3 = 1$, and $q_4 = 3$, the flows to the market at maximum (steady-state) production are given by

$$q_1^m = \max(0, q_1 - q_2^{in} - q_3^{in})$$
$$q_i^m = q_i, \quad i = 2, 3, 4$$

where q_i^{in} is the inflow to area i and q_p^m denotes the flow to market of product p. If the conversion between raw material and product in the areas is 1:1, this gives the flows to the market

$$q^m = [\,1 \;\; 2 \;\; 1 \;\; 3\,]^T$$

The contribution margins for the products in the example are

$$p = [\,1 \;\; 2 \;\; 4 \;\; 1\,]^T$$

Utility Measurement Data The example site requires the five utilities: steam, cooling water, electricity, feed water and instrument air. The corresponding utility parameters, that determine if the utility works correctly, are 'pressure' for steam, feed water and instrument air, and 'temperature' for cooling water. Electricity can only be operating or not operating, i.e. 'on' or 'off'. The measurements of the utility parameters during 10 hours with the sampling interval 1 hour are given below

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

The disturbance limits that have been set for these utilities at the site are:

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

which gives the utility operation matrix

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

Utility Requirements Table 1 shows the utilities that are required by each area in this example.

Table 1. Utilities required at each area.

	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

This gives the area-utility matrix

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

8.2 Utility Availability

Using (1) we get the utility availabilities

$$U_{av} = U \cdot \mathbf{1}/n_s = [\,0.7\ 0.8\ 0.9\ 0.8\ 0.8\,]^T$$

for the example site, if there are no planned stops in the data set.

Utility Dependence A flowchart of the interdependence between the utilities in the example is given in Fig. 2.

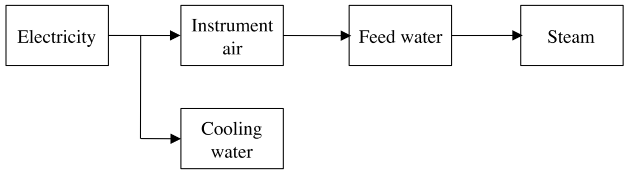

Fig. 2. Utility dependence flowchart.

The utility dependence matrix becomes

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

We get the utility operation matrix

$$U_{ud} = \begin{bmatrix} 1\,1\,1\,0\,1\,1\,1\,1\,1\,1 \\ 1\,1\,1\,1\,0\,0\,1\,1\,1\,1 \\ 1\,1\,1\,1\,1\,1\,0\,1\,1\,1 \\ 1\,0\,0\,1\,1\,1\,1\,1\,1\,1 \\ 1\,1\,1\,1\,1\,1\,1\,0\,0\,1 \end{bmatrix}$$

when utility dependence is taken into account. This gives the utility availabilities

$$U_{av}^{ud} = U_{ud} \cdot \mathbf{1}/n_s = [\,0.9\ 0.8\ 0.9\ 0.8\ 0.8\,]^T$$

8.3 Area Availability

Using (3) and (5) the direct and total availabilities become

$$A_{av}^{dir} = [\,0.4\ 0.7\ 0.2\ 0.7\,]^T$$
$$A_{av}^{tot} = [\,0.4\ 0.2\ 0.2\ 0.7\,]^T$$

8.4 Estimation of Revenue Loss for each Product

An estimate of the direct and total revenue loss for each product is given by (7) and (8). We get

$$J_p^{dir} = [\,6\ 12\ 32\ 9\,]^T$$
$$J_p^{tot} = [\,6\ 32\ 32\ 9\,]^T$$

Consequently, area 2 and 3 for the greatest total loss at the site and seems to be most vulnerable to utility disturbances.

8.5 Estimation of Revenue Loss due to each Utility

An estimate of the direct and total revenue loss due to each utility is given by (9) and (10). We get

$$J_p^{dir} = [\,5\ 16\ 12\ 10\ 16\,]^T$$
$$J_p^{tot} = [\,9\ 16\ 12\ 18\ 24\,]^T$$

This shows that instrument air causes the greatest total loss at the site, which could be useful to know e.g. when deciding where to focus maintenance efforts.

9. A TOOL FOR DISTURBANCE MANAGEMENT

A simple Matlab function for estimating the revenue losses due to utilities has been developed by the authors. This tool can be used for any site by defining the equipment hierarchy of the site, when the site and its utilities are represented by matrices, as described in Section 7. The inputs to the function are the equipment hierarchy of the site, utility measurement data, the interdependence of utilities, and the requirements of utilities in different areas. The function returns utility and area availabilities, estimates of the revenue losses caused by each utility at the site, and estimates of the loss corresponding to each product due to utility disturbances. The estimates are obtained using on/off production modeling, as described in this paper. In Matlab, the tool is run by

```
[Uav,Adirav,Atotav,Jdirp,Jtotp,Jdiru,Jtotu]=...
                     = Tool_1(U,U_d,A_d,A_u,q_m,p)
```

using the notation from Section 7. This is a tool that may be used for proactive disturbance management: The tool gives guidelines regarding for which utilities improvement efforts would be most profitable. An advantage with this tool is that it gives quick results with very little modeling effort. A disadvantage is that it only gives relative results: ordering of utilities according to the revenue loss they cause. If also reactive disturbance management strategies are desired, such as giving guidelines on how to react to certain utility disturbances, a more advanced tool is required.

10. AN INDUSTRIAL EXAMPLE

The utility disturbance management tool has been used for the site at Perstorp studied in Lindholm et al. (2011a). This site has 10 areas and 14 utilities. Measurement data from August 1, 2007 to July 1, 2010 was used, with a sampling interval of 1 minute. There was a planned stop between September 15 and October 8, 2009. This gives the size (14×1501921) of the utility operation matrix. The estimates of the revenue losses for this example are computed by the Matlab script in less than one minute.

At the beginning of the case study, a survey was performed at the site, where operators where asked questions about their perception of the frequency and severity of different utility disturbances. The results from this survey seem to agree well with the results from the utility disturbance management tool.

11. CONCLUSION

The suggested tool may be used to give decision support on where proactive disturbance management efforts should be focused at a site. The tool is easy to apply to any process industrial site and can handle large sets of measurement data. The tool uses matrices that represent the site structure, utility measurement data, interdependence of utilities, and requirements of utilities at different areas.

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