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Formulating an Optimization Problem for Minimization of Losses due to Utilities

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Abstract: Utilities, such as steam and cooling water, are often shared between several production areas at industrial sites, and the effects of disturbances in utilities could thus be hard to predict. In addition, production areas could be connected because of the product flow at the site. This paper introduces a simple modeling approach for modeling the relation between utility operation and production. Using this modeling approach, an optimization problem can be formulated with the objective to minimize the economical losses due to disturbances in utilities by controlling the production of all areas at a site. The formulation of the problem is general, and thus the optimization can be performed for any site with similar structure. The results are useful for investigating the impact of plant-wide disturbances in utilities, and can provide decision support for how to control the production at utility disturbances. To enable online advise to operators on how to control the production, the posed optimization problem is solved in receding horizon fashion.

Keywords: Enterprise modelling; Optimization problems; Production control; Utility; Chemical industry; Model-based control; Decision support systems.

1. INTRODUCTION

Complex chemical plants are often hard to model in detail (Kano and Nakagawa (2008)), and for some applications, a detailed model might not be needed. In this paper, disturbances in utilities, that affect one or more production areas at a site, are studied. These disturbances are important to handle well since utility costs often represent a large part of the total operating cost of chemical plants (Iyer and Grossmann (1998)). The objective in this study is to determine how the production in all areas at a site should be controlled at disturbances in the supply of utilities in order to minimize the economical effects. Buffer tanks or inventories at the site should also be used optimally to achieve this. The key idea is to model the network of areas at a site without including detailed complex dynamics within each area. Modeling of a site at a similar abstraction level is performed in Wassick (2009). However, in Wassick (2009) the focus is on production planning and scheduling on a longer time horizon, and not on real-time disturbance management as in this paper.

Utilities have been studied by several researchers, but mainly, the focus has been on the synthesis of utilities to satisfy a given demand. Work within this area includes among others Papoulias and Grossmann (1983), Hui and Natori (1996), Maia et al. (1995), Velasco-Garcia et al. (2011), Iyer and Grossmann (1998) and Wilkendorf et al. (1998). In most of these studies, the synthesis problem has been formulated as a mixed-integer linear program (MILP). Mainly, the focus in these papers are on utilities for heat and power production. The present study enables consideration of other utilities, such as nitrogen and instrument air, as well. The objective in this study, as opposed to previous studies, is to determine how the utility resources should be divided among the production areas of a site at each time instance, to minimize economical losses. This could be seen as to determine how to transfer the variability of a process from sensitive locations to locations where it does less damage, as discussed in Qin (1998) and Luyben et al. (1999).

In order to optimize the supply of utilities to each area, the effect of utility disturbances on production has to be modeled. Modeling of utilities may be very complex, but if only the utilities' effect on production is relevant, a detailed model might not be needed. In this paper, a simple modeling approach is suggested based on the assumption that utility resources may be interpreted as volumes or power, which is shared by the production areas. A linear relation between assigned utility volume and maximum possible production in an area is assumed. This representation is used to formulate an optimization problem for minimizing the economical losses due to utility disturbances. The formulation of the optimization problem is similar to the formulation in Kondili et al. (1993) for scheduling of batch operations. However, in the present study, the use of integer variables has been avoided and a quadratic cost function has been used, with the objective to produce solutions that are more robust to parameter changes.

A receding horizon formulation of the optimization problem is used to enable online advice to plant operators, given an estimated disturbance trajectory. A cost function that aims to reduce the revenue loss due to disturbances is designed, with weights that could be chosen to find a good trade-off between keeping the buffer tank levels at the site at desirable levels, and maximizing profit.

2. ROLE-BASED EQUIPMENT HIERARCHY

According to the standard ISA-95.00.01 (2009), a site consists of one or more production areas, where each area produces either end products or intermediates. The intermediate products may either be sold on the market or refined to end products in other areas at the site. Buffer tanks could be placed between areas to serve as inventory of the intermediates or as buffer tanks with the purpose to allow independent operation of upstream and downstream areas. Thus, the production at a site may be viewed as a network of areas, with intermediate buffer tanks between some areas. An example is given in Fig. 1.

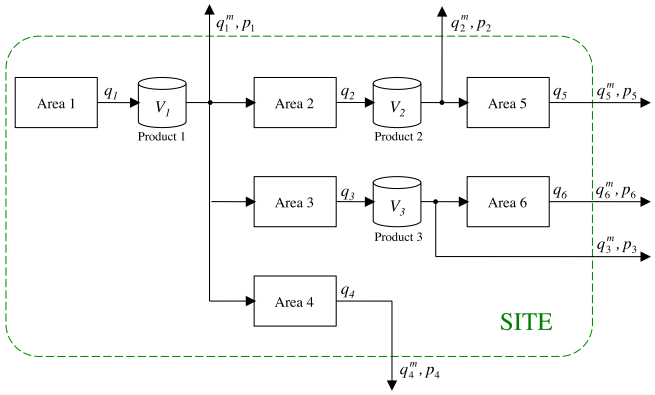

Fig. 1. An example of a site hierarchy.

In this paper, the dynamics of production areas are ignored, i.e. it is assumed that the production of an area is directly proportional to the inflow to the area, i.e.

$$q_j^{\text{in}} = q_j y_{ij} \tag{1}$$

where q_j^{in} is the inflow of product i to area j, q_j the production of area j, and y_{ij} is denoted the conversion factor between product i and product j. This assumption is reasonable since the area dynamics are usually fast compared to the dynamics of the production network.

3. MODELING OF UTILITIES

Utilities are support processes that are utilized in production, but that are not part of the final product. Common utilities include steam, cooling water, electricity, compressed air, and water treatment. Some of these utilities operate continuously, such as steam, cooling water, feed water and vacuum systems, whereas some utilities have on/off characteristics. Examples of such utilities are electricity and nitrogen.

The measurements related to utilities are often parameters like temperature, flow or pressure of the utility. The mapping from these measurements of utility properties to the constraints it imposes on production is not trivial, and might look different for different utilities. Thus, operation outside its normal limits might give very different effects on the production of the areas that require the utility. Furthermore, a utility might be shared between several production areas. If the effects of disturbances in utilities at an entire site should be studied, this must also be modeled in some way.

The suggestion in this paper is to represent the utilities as volumes, or power, which all areas that require the utilities have to share. This interpretation makes sense for example for cooling water and steam utilities, where all areas that require these utilities have to split the total cooling or heating power. The amount of a utility that an area is assigned is assumed to give a constraint on the production of the area according to

$$q_j \leq c_{ij} u_{ij} + m_{ij} \tag{2}$$

where $q_j \geq 0$ is the production of area j, $u_{ij} \geq 0$ the assignment of utility i to area j and $c_{ij} \geq 0$ and $m_{ij} \geq 0$ are constants. If $c_{ij} > 0$, this model should correspond quite well to many utilities with continuous characteristics. For example, for cooling water: The cooling water utility produces a certain cooling power, that is shared between production areas that are connected to the cooling water system. If an area is assigned more cooling water power, it should be able to produce at a higher production speed, within the normal range of production rates. The constraint in (2) is presented graphically for $m = 0$ and some $c_{ij} > 0$ in Fig. 2.

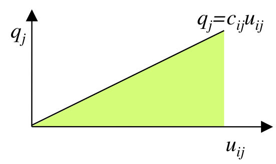

Fig. 2. A continuous utility's constraints on production.

If $c_{ij} = 0$, (2) corresponds to representation of a utility with on/off characteristics, where the area can produce at some maximum speed if the supply of utility is greater than zero, and not at all when it does not get assigned any amount of the utility. This is represented in Fig. 3.

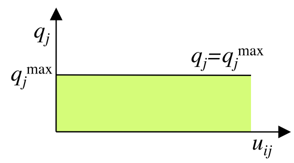

Fig. 3. An on/off utility's constraints on production.

In reality, there could be a minimum amount of a utility that is required for a production area to be able to operate, here denoted u_{ij}^{min}. Also, there could be an upper limit, u_{ij}^{max}, such that supplying more utility than u_{ij}^{max} does not permit higher production than the maximum possible production if u_{ij}^{max} is assigned to the area. This modification to the constraint in (2) could be captured by setting maximum and minimum constraints on the production rates. If these constraints are taken into account, the representation of the continuous type and on/off type utilities become as in Fig. 4.

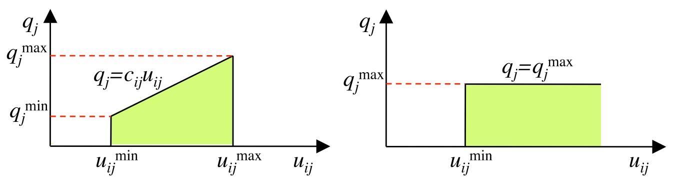

Fig. 4. Utility representations with production constraints.

As mentioned previously, utilities are often shared between several production areas at a site. The volume representation of utilities makes it possible to represent this by constraints of the form

$$\sum_j u_{ij} \leq U_i, \quad i = 1, \ldots, n_u \tag{3}$$

where u_{ij} is the amount of utility i assigned to area j, U_i is the total amount of utility i, and n_u the number of utilities used at the site. This is used to formulate the optimization problem in Section 4.

4. FORMULATING THE OPTIMIZATION PROBLEM

The formulation of the optimization problem for minimizing the economical effects of disturbances in utilities consists of defining the model and the constraints, and shaping the objective function. The input to the optimization is estimated utility disturbance trajectories over the prediction horizon, i.e. an estimation of the total available amount of all utilities, $U_i(t)$, at each time t. After having defined the optimization problem, the problem is solved in receding horizon fashion to enable online use. The optimization results can be used as online advice to operators or, if possible, applied directly to form closed loop model predictive control (MPC).

4.1 Model

The model of the site is given by the connections of its production areas. An example of what the site structure could look like is given in Fig. 1. The connections of areas are represented by the mass balances at the internal buffer tanks, i.e.

$$V_i(t+1) = V_i(t) + q_i(t) - q_i^m(t) - \sum_{j \in \mathcal{N}_i} q_j(t) y_{ij}, \quad i = 1, \ldots, n_b \tag{4}$$

where $V_i(t)$ is the volume in the buffer tank for product i at time t, $q_i(t)$ the production of product i at time t, $q_i^m(t)$ the flow to the market of product i at time t, and y_{ij} the conversion factor between product i and j (see (1)). $\mathcal{N}_i$ is the set of areas directly downstream of area i, and n_b is the number of internal buffer tanks.

4.2 Constraints

Constraints are imposed on buffer tanks and production rates. Disturbances in the supply of utilities give time-varying constraints on production rates.

Buffer Tanks The levels in the buffer tanks have to be kept between some high and low limits, i.e. we have

$$V_i^{\min} \leq V_i(t) \leq V_i^{\max}, \quad i = 1, \ldots, n_b \tag{5}$$

The maximum and minimum limits, $V^{\max}$ and $V^{\min}$, might correspond to the entire buffer tank, or it could correspond to a part of the tank that is reserved for handling disturbances in utilities.

Production Rates Limited capacity of production areas give upper constraints on the production rates, $q^{\max}$. There is also a minimum rate at which an area could operate, $q_{\min}$, which could be greater than zero. Shutdown and start-up of areas is often very expensive and should be avoided. One way to model this is to impose a soft constraint on the production rates. The way this is done is by introducing a slack variable, s_i, such that

$$q_i^{\min} + s_i(t) \leq q_i(t) \leq q_i^{\max} \tag{6}$$

$$-q_i^{\min} \leq s_i(t) \leq 0 \tag{7}$$

The slack variable is penalized in the objective function to avoid shutdown of areas, if it is not necessary.

An alternative way of doing this is to use integer variables and punish shut-down of areas in the objective function. This is done for penalizing shutdown/start-up of different utility generation units in Iyer and Grossmann (1997) and Velasco-Garcia et al. (2011), which results in a mixed-integer linear program.

Utilities At a disturbance in the supply of a utility, the available amount of the utility might not be enough to supply all areas with the amount they need for maximum production. If utilities are modeled according to Section 3, this constraint is represented by requiring (3) to hold for all times t, e.g.

$$\sum_{j \in \mathcal{M}_i} u_{ij}(t) \leq U_i(t), \quad i = 1, \ldots, n_u \tag{8}$$

where $u_{ij}(t)$ is the amount of utility i that is assigned to area j at time t, $U_i(t)$ is the total amount of utility i available at time t, and n_u the number of utilities used at the site. $\mathcal{M}_i$ is the set of areas that require utility i. If (2) holds for all areas j and utilities i, these constraints become time-varying constraints of the production rates of all areas that share a utility, since $U_i(t)$ varies over time. It can be assumed that equality holds in (2) since it would not be optimal for an area to not use all its assigned utility volume to produce its product, as the production in other areas might be limited by the same utility. For continuous utilities, (8) can be rewritten using (2) as

$$\sum_{j \in \mathcal{M}_i} k_{ij} q_j(t) - d_{ij} \leq U_i(t), \quad i = 1, \ldots, n_{uc} \tag{9}$$

where $k_{ij} = 1/c_{ij}$ and $d_{ij} = m_{ij}/c_{ij}$ are positive constants for utility i, area j. n_{uc} is the number of utilities of continuous type.

For on/off utilities, (2) becomes equivalent to the maximum constraint on the production rate, (6). The areas that require the utility can operate at maximum speed at time t if the utility is available at time t, and can not operate if the utility is unavailable. This constraint may be written as

$$q_j(t) = \begin{cases} q_j^{\max} & \text{if } U_i(t) = 1 \quad j \in \mathcal{M}_i \\ 0 & \text{if } U_i(t) = 0, \quad i = n_{uc}+1, \ldots, n_u \end{cases} \tag{10}$$

if all utilities all utilities at the site are either of continuous or on/off type.

4.3 Objective Function

Before the dynamic optimization problem can be cast, reference values need to be computed. The production and the flows to the market that give the optimal profit, p_{ref}, is determined by a steady-state optimization, i.e. by assuming that there are no disturbances in utilities, and no buffer tanks between areas. The optimal production rates and flows to the market and the optimal profit from the steady-state optimization are used as a reference values for the dynamic optimization, where the objective is to minimize the economical effects of disturbances in the supply of utilities. The dynamic optimization is given an estimated disturbance trajectory some steps ahead, and the problem is solved in receding horizon fashion. The optimization result is used as advice to the operators at the site on how to control the production.

Steady-state Optimization If there are no disturbances, and no buffer tanks between areas, the optimal profit can be determined by the linear program

$$\begin{aligned} p_{\text{ref}} = &\text{ maximize } p^T q^m \\ &\text{subject to } (4), (6), (7) \end{aligned} \tag{11}$$

with variables q, q^m and s, where p contains the contribution margins of all products, and q^m the flows to the market of all products. The flows that give the optimal profit are denoted q_{ref}, q^m_{ref}.

Dynamic Optimization Based on the solution to the steady-state optimization problem and reference levels V_{ref} for the buffer tanks, we form the following objective function

$$J(\mathbf{q}, \mathbf{q}^m, \mathbf{V}, \mathbf{s}) = \sum_{\tau=0}^{N-1} J_t\left(q(\tau), q^m(\tau), V(\tau), s(\tau)\right) \tag{12}$$

with variables

$$\begin{aligned} \mathbf{q} &= \left[q(0)^T \ \ldots \ q(N-1)^T\right]^T \\ \mathbf{q}^m &= \left[q^m(0)^T \ \ldots \ q^m(N-1)^T\right]^T \\ \mathbf{V} &= \left[V(0)^T \ \ldots \ V(N-1)^T\right]^T \\ \mathbf{s} &= \left[s(0)^T \ \ldots \ s(N-1)^T\right]^T \end{aligned}$$

and

$$\begin{aligned} J_t\left(q(t), q^m(t), V(t), s(t)\right) = &\left(p^T q^m(t) - p_{\text{ref}}\right)^2 Q_p \\ &+ \Delta V^T(t) Q \Delta V(t) \\ &+ \Delta q^T(t) R \Delta q(t) \\ &- g^T s(t) + s^T(t) Q_s s(t) \end{aligned}$$

with

$$\begin{aligned} \Delta V(t) &= V(t) - V_{\text{ref}} \\ \Delta q(t) &= q(t) - q_{\text{ref}} \end{aligned}$$

$Q_p > 0$ is a scalar weight, g a positive weighting vector, and Q, R, and Q_s are positive definite weighting matrices. The optimization problem becomes

$$\begin{aligned} &\text{minimize } J(\mathbf{q}, \mathbf{q}^m, \mathbf{V}, \mathbf{s}) \\ &\text{subject to } (4), (5), (6), (7), (9), (10) \end{aligned} \tag{13}$$

The objective function consists of four parts:

- $(p^T q^m(t) - p_{\text{ref}})^2 Q_p$

  To penalize deviation from the reference profit.

- $\Delta V^T(t) Q \Delta V(t)$

  To penalize deviations from reference buffer tank levels, to avoid solutions where all inventories are sold.

- $\Delta q^T(t) R \Delta q(t)$

  To penalize deviations from nominal production.

- $-g^T s(t) + s^T Q_s s(t)$

  To inflict extra cost to area shutdown.

The constraints (9) and (10) have to be supplied with an estimate of the available amount of each utility at each time step, $U_i(t)$. Initial conditions $V(0)$ to (4) are given from measurements. The optimization problem (13) is solved in receding horizon fashion, or when operators need advice.

The posed optimization problem has a structure that makes it possible to solve it in a distributed fashion. Therefore, the solution method presented in Giselsson et al. (2011) is used to solve the problem.

5. AN EXAMPLE

In this section, the optimization problem formulation presented in Section 4 is used to formulate and solve a specific problem. The site that is considered is the site with six production areas given in Fig. 1. Table 1 summarizes the maximum and minimum production rates of all areas, $q^{\max}$ and $q^{\min}$, the contribution margins of all products, p, the maximum and minimum volume of all buffer tanks, $V^{\max}$ and $V^{\min}$, and the reference volumes for the buffer tanks, V_{ref}.

Table 1. Production data.

	$q^{\min}$	$q^{\max}$	p	$V^{\min}$	$V^{\max}$	V_{ref}
Product 1	0.10	1	0.4	0	0.5	0.5
Product 2	0.05	0.5	0.7	0	0.5	0.5
Product 3	0.02	0.2	0.1	0	0.5	0.5
Product 4	0.01	0.1	0.5	-	-	-
Product 5	0.02	0.2	0.8	-	-	-
Product 6	0.02	0.2	1.0	-	-	-

Three utilities are considered at the example site; high pressure (HP) steam, middle pressure (MP) steam, and cooling water. Table 2 shows which utilities that are required at each area. It is assumed that, at maximum production, the utilities are shared equally between the areas that require them.

Table 2. Utilities required at each area.

Area →	1	2	3	4	5	6
Steam HP	x		x			
Steam MP		x		x		x
Cooling water	x	x	x	x	x	x

5.1 Model

The mass balances at all buffer tanks at the site give

$$\begin{aligned} V_1(t+1) = &V_1(t) + q_1(t) - q_1^m(t) \\ &- q_2(t) - q_3(t) - q_4(t) \end{aligned} \tag{14}$$

$$V_2(t+1) = V_2(t) + q_2(t) - q_2^m(t) - q_5(t) \tag{15}$$

$$V_3(t+1) = V_3(t) + q_3(t) - q_3^m(t) - q_6(t) \tag{16}$$

As can be seen in the equations, all conversion factors, y_{ij}, are chosen to be equal to one in the example, for simplicity.

5.2 Constraints

Buffer Tanks Upper and lower level constraints are given by (5) for the three buffer tanks, $i = 1, 2, 3$. The limits $V^{\max}$ and $V^{\min}$ are given in Table 1.

Production Rates Minimum and maximum limitations on production rates give constraints according to (6) and (7), where also slack variables are introduced to be able to penalize shutdown of areas. The limits $q^{\max}$ and $q^{\min}$ are given in Table 1.

Utilities It is assumed that the total amount of each utility is equal to one ($U_1 = U_2 = U_3 = 1$) when it operates at maximum capacity. The utilities in the example are of continuous type (see Section 3), and it is assumed that zero assignment of a utility to an area gives zero production, i.e. $c_{ij}, k_{ij} > 0$ and $m_{ij} = d_{ij} = 0$ for all utilities i and areas j. The time-varying constraints on the production rates due to shared utilities are obtained from (9) using Table 2. We get

$$k_{11}q_1(t) + k_{13}q_3(t) \le U_1(t) \tag{17}$$

$$k_{22}q_2(t) + k_{24}q_4(t) + k_{26}q_6(t) \le U_2(t) \tag{18}$$

$$\sum_{i=1}^{6} k_{3i}q_i(t) \le U_3(t) \tag{19}$$

where $U_i(t)$ is equal to one if utility i operates at maximum capacity at time t, and less than one otherwise. Since the utilities in the example are shared equally at maximum production, we get

$$k_{11} = \frac{1}{2q_1^{\max}}, \quad k_{13} = \frac{1}{2q_3^{\max}} \tag{20}$$

$$k_{22} = \frac{1}{3q_2^{\max}}, \quad k_{24} = \frac{1}{3q_4^{\max}}, \quad k_{26} = \frac{1}{3q_6^{\max}} \tag{21}$$

$$k_{3i} = \frac{1}{6q_i^{\max}}, \quad i = 1, \ldots, 6 \tag{22}$$

5.3 Objective Function

Since the flows to the market from the end product areas are the same as the production in these areas, the flows to the market from end product areas are omitted in the optimization. Merging the production of all areas, and the flows to the market of intermediate products to one decision variable vector, we get

$$\bar{q} = [\, q_1 \; q_2 \; q_3 \; q_4 \; q_5 \; q_6 \; q_1^m \; q_2^m \; q_3^m \,]^T \tag{23}$$

The extended contribution margin vector becomes

$$\bar{p} = [\, 0 \; 0 \; 0 \; p_4 \; p_5 \; p_6 \; p_1 \; p_2 \; p_3 \,]^T \tag{24}$$

Steady-state Optimization The steady-state solution that maximizes (11) becomes

$$\bar{q}_{\text{ref}} = [\, 1 \; 0.5 \; 0.2 \; 0.1 \; 0.2 \; 0.2 \; 0.2 \; 0.3 \; 0 \,]^T \tag{25}$$

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

Dynamic Optimization The MPC problem formulation for dynamic optimization is posed as (13) with constraints (5)–(7) and (14)–(19). s consists of six slack variables that are included to prevent unnecessary shutdown of area 1-6.

The weights for the optimization are in the example chosen as $Q_p = 100$, $R = \text{diag}([\, 0.1 \; 0.1 \; 0.1 \; 10 \; 10 \; 10 \; 10 \; 10 \; 10 \,])$, $Q = I_3$, $g = 100q^{\max}$, $Q_s = I_6$. The prediction horizon was chosen as $N = 10$.

5.4 Results

Estimating the disturbance trajectory ten steps ahead and using the MPC formulation gives trajectories that suggest how the production should be controlled to minimize the economical effects of the disturbance. The solution trajectories of the example problem for a disturbance in middle pressure steam is given in Fig. 5. In this example, it is assumed that the actual disturbance trajectory is identical to the estimated trajectory. To give a clearer view of how the disturbance is handled, the production and the sales at the time of the disturbance are shown in Fig. 6.

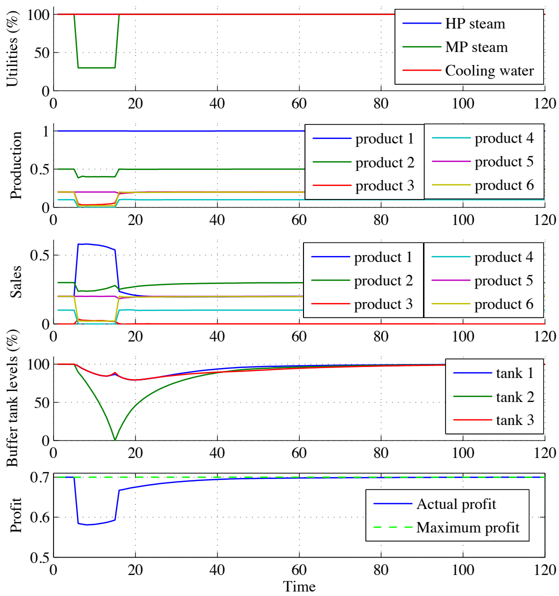

Fig. 5. Optimal trajectories for MP steam disturbance.

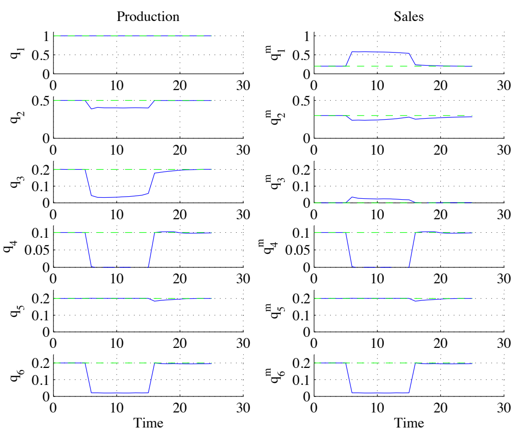

Fig. 6. Optimal production and sales trajectories at MP steam disturbance (solid blue lines) compared to optimal steady-state solution (dashed green lines).

6. CONCLUSIONS

A simple modeling approach for modeling the effects of utility disturbances on production was introduced, that can represent both continuous and on/off type utilities. This representation allows formulation of an optimization problem that aims to find production trajectories that minimize the revenue loss due to disturbances in utilities, when utilities are shared between one or more production areas. The optimization results can be used to analyze the effects of different plant-wide disturbances in utilities, or to get advice on how to handle different types of disturbances in utilities given certain constraints on the production and the buffer tanks at the site. In addition, the trade-off between keeping buffer tank levels at reference levels and maximizing the profit can be studied by manipulating the weights of the cost function for the optimization problem.

To enable online advice to site operators on how to control the production at utility disturbances, the optimization problem can be solved in receding horizon fashion, where the disturbance trajectories estimated over the prediction horizon are given as input to the optimization. These predicted disturbance trajectories may be updated in each time step, which may be useful if new information about the disturbance becomes available.

7. FUTURE WORK

Something that is not considered in the optimization problem formulation is market constraints. A possible future work direction is to include the supply chain, e.g. market demand and transports, in the problem formulation. It would also be interesting to further investigate the robustness of the solution, i.e. how the behavior of the system is affected when the estimated disturbance trajectory is not exactly the same as the actual disturbance trajectory. A comparison of the suggested approach with a MILP formulation, robust MPC and stochastic programming should be valuable to assess the performance and efficiency of the proposed approach.

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