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Integrated scheduling of batch production and utility systems for provision of control reserve

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Abstract:
Control reserve is becoming increasingly important due to the increase of fluctuating renewable energy. Today, control reserve is mostly provided by large fossil-based power plants. In the future, control reserve has to be provided increasingly by decentralized utility systems. The main purpose of these utility systems is to supply energy to production systems. However, production systems are commonly scheduled without considering control reserve. Only subsequently, the utility system is scheduled to supply the production system with energy and for potential provision of control reserve. This sequential approach misses synergistic opportunities between production and utility systems.
In this contribution, we propose a method for integrated scheduling of utility and production systems with provision of control reserve. The integrated scheduling identifies production schedules offering potential to provide control reserve by the utility system. Uncertainty of control-reserve request is modeled by stochastic programming. The production schedule is fixed after the integrated scheduling and also not changed if control reserve is requested. In this case, only the utility system changes its operation.
Our method is applied to a case study considering a batch production system and the utility system, which are scheduled for one day of operation. Compared to the sequential scheduling with consideration of control-reserve provision, our method saves additional $3.3\,\%$ of operational expenditures. Thus, integrated scheduling of production and utility system for control-reserve provision is highly beneficial and the presented method identifies this potential in practice.

Keywords:
Balancing power, Ancillary service, MILP, Energy system, Stochastic programming

1. Introduction

In many countries, electricity from fluctuating renewable energies is increasing over the past years [1]. Fluctuating electricity supply is difficult to predict [2]. Both the fluctuations and the prediction errors are challenging for the required balance of supply and demand. Supply and demand are ultimately balanced by control reserve.
Control reserve is a balancing service, which is offered by electricity providers or consumers. The providers or consumers offer to shortly increase or decrease their electricity production or consumption depending on grid requirements, respectively.
Nowadays, control reserve is mainly supplied by large-scale power plants. However, power plants are shut down to mitigate climate change and electricity is increasingly supplied by decentralized

electricity providers. As a result, the decentralized electricity providers also need to increasingly participate in the markets for control reserve [3]. These decentralized providers of control reserve are utility systems [4], production systems such as aluminum electrolyzers [5] or air separation plants [6]. Even renewable energies are considered to provide control reserve [7].

Control-reserve provision by utility systems has therefore been investigated in literature. Muche et al. [8] model the participation of a biomass-fueled combined-heat-and-power plant in the positive tertiary reserve market. The authors assumed an average price for provision of control-reserve capacity and request of control-reserve energy. If control reserve is requested, Muche et al. [8] ensure feasibility by storing excess heat to be used another day. The size of the heat storage is unlimited during optimization. The investment cost are only evaluated after optimization and, consequently, the storage size is not optimal.

Kumbartzky et al. [4] model a combined-heat-and-power plant with a flexible power-to-heat ratio to participate in the tertiary reserve market and the day-ahead spot market. The uncertain prices in both markets are considered in a multi-stage stochastic programming model. Scenarios are modeled for the reserve capacity price and the spot market price. No energy price is considered for requested control reserve based on the assumption that the request of control reserve has a low probability.

Control reserve cannot only be provided by electricity providers but also by electricity consumers such as production systems [9]. Zhang et al. [6] model a continuously operated production system and provide control reserve by interruptible load. The uncertainty of request is considered by robust optimization. Schäfer et al. [5] consider the participation in the control-reserve market for an energy-intensive process. The authors propose a decomposition method, where the two-stage stochastic program is divided in two optimization problems. The two optimization problems are a nonlinear problem for the bidding strategy and a mixed-integer linear problem to schedule the production process.

The previously reviewed articles considered continuously operated production systems, which are assumed to interrupt their production process or to transition into part-load operation. However, batch processes can often not be interrupted or operated in part-load. Thus, the batch production schedule is usually fixed and cannot be changed if control reserve is requested. Consequently, the reviewed methods are not applicable for batch production systems. In this work, we provide a method that allows for provision of control reserve without changing the production schedule of the production system if control reserve is requested. Thus, the method is applicable for batch production systems.

For batch production scheduling without consideration of control reserve, the integrated scheduling of batch production and utility systems has been shown to be beneficial [10; 11]. Thus, it seems desirable to expand the integrated optimization for the provision of control reserve by utility systems. Such an integrated optimization could schedule the production system to allow the utility system to increase the profit in control-reserve provision.

In this contribution, we propose a method for the integrated scheduling of batch production and utility systems from control-reserve provision. We consider batch production systems which can neither interrupt their batches nor run them in part-load. Thus, we identify a production schedule which remains fixed during a request of control reserve. Still, the fixed production schedule from the integrated scheduling leads to an energy demand that allows the utility system to increase profits from control-reserve provision compared to the common sequential scheduling.

2. Integrated scheduling for provision of control reserve

In this section, we present a method for scheduling batch production and utility systems to participate in control-reserve market. The method is intended for the frequent scheduling of production systems, e.g., daily production scheduling.

Commonly, production and utility systems are optimized by sequential scheduling: first, the production system is scheduled. As a result, the corresponding energy demand is known. Subsequently, the utility system is scheduled for the given energy demand. This subsequent scheduling of the utility

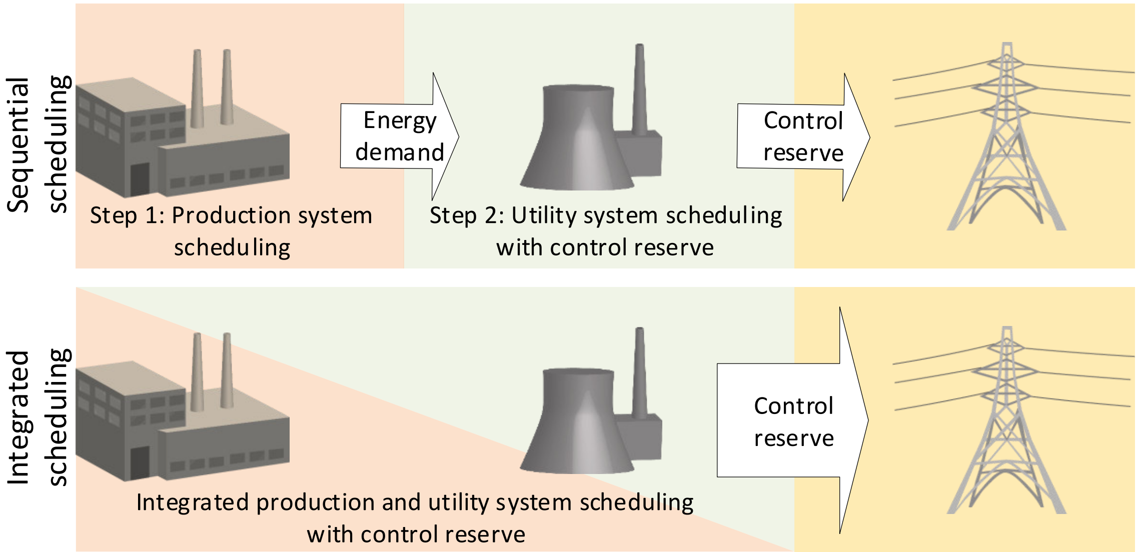

Figure 1: Sequential and integrated scheduling of production and utility system. In sequential scheduling, first, the production system is scheduled for the minimal production cost. Subsequently, the utility system is scheduled to provide the energy demand of the production system as well as control reserve to the grid. The integrated scheduling considers the production and utility system simultaneously.

system also optimizes the participation in control-reserve markets. In our method, we overcome the sequential scheduling by simultaneously scheduling production and utility systems while optimizing the participation of the utility system in the control-reserve market (Figure 1). Our method assumes that the requested control-reserve energy is provided by changing the operation of the utility system since the production schedule is fixed. The integrated scheduling identifies the production schedule that is optimal for the provision of control reserve by the utility system.

Our method takes the probability of control-reserve request into account in a stochastic optimization problem with three scenarios: 1. Positive control reserve is requested (POS), 2. Negative control reserve is requested (NEG), 3. No control reserve is requested (NO).

In Section 2.1., we state the problem for providing control-reserve capacity in control-reserve markets and explain the stochastics of the considered problem. In Section 2.2., we model the integrated scheduling with control-reserve provision. Here, we focus on the extensions compared to the modeling without control-reserve provision.

2.1. Stochastic problem of control-reserve provision

The method uses a stochastic programming model for the participation in the control-reserve market. Here, we consider the control-reserve market as pay-as-bid market, e.g., in the German and French tertiary control-reserve markets [12].

The method considers the provision of both positive and negative control reserve. Positive control reserve is requested if insufficient electricity is supplied to the grid. Consequently, the electricity supply needs to be increased or the electricity demand decreased. If negative control reserve is requested, supply needs to be decreased or demand needs to be increased.

Our method considers a control-reserve market where offers contain two prices: the capacity price for providing control-reserve capacity and the energy price for actually delivering control reserve. The offers are ordered by the capacity price in a merit order. All offers are accepted in the merit order until the demand of control-reserve capacity is met. The offered capacity price is paid for every accepted offer. Subsequently, the accepted offers are ordered by their energy price in a second merit order. If control reserve is needed, control reserve is activated in the order of the second merit order. These market mechanics correspond, e.g., to the tertiary control-reserve market in Germany [13].

Our method optimizes the participation of an integrated batch production and utility system in a control-reserve market by optimizing the offered control-reserve capacity and the energy price for

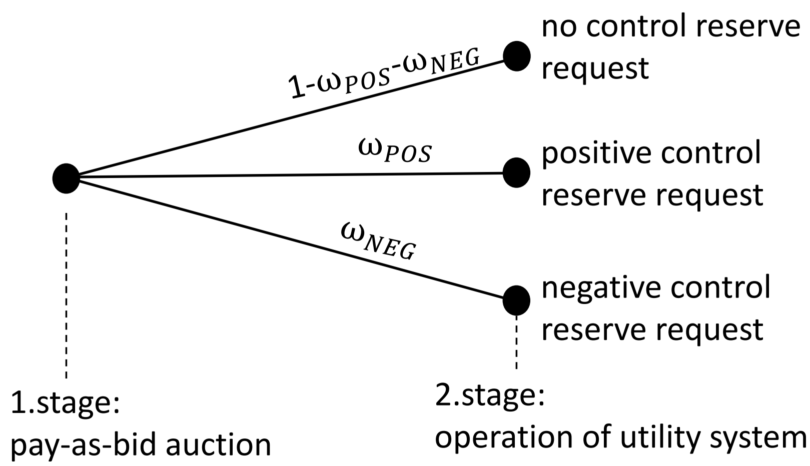

Figure 2: Stochastic process of the two-stage stochastic programming model. On the 1. stage, the amount of provided control-reserve capacity and the energy price for delivered control reserve are decided. On the 2. stage, the operation of the utility system needs to be decided, depending on whether positive, negative or no reserve energy is requested. The scenarios are considered with their corresponding probabilities: ω_{NEG}, ω_{POS} and (1-ω_{POS}-ω_{NEG}).

the actual delivered control reserve. Requested control reserve is delivered by adapting the operation of the utility units while the electricity demand or supply to the grid meets the control-reserve request. In the method, we optimize the offered control-reserve capacity and energy price. To identify the optimal offer, we take into account the probability of control-reserve request. The probability of control-reserve request depends on the offered energy price.

We model the uncertainty of request by a two-stage stochastic programming model [14]. First-stage decisions are the amount of control-reserve capacity provided, the offered energy price and the schedule of the production system (Figure 2). Second-stage decisions correspond to the actual operation of the utility system in each of the three scenarios for control-reserve request (positive, negative, none). Both stages are coupled by the energy demand. The energy demand of the production system is determined in the first stage, while the actual operation of the utility system to fulfill the energy demand depends on the request scenario. Furthermore, the amount of provided control-reserve capacity and energy price has to be decided before it is known if the control-reserve capacity is actually requested or not. Thus, the provided control-reserve capacity is considered by non-anticipativity constraints. Non-anticipativity constraints model that some decisions need to be taken at a certain time based only on the current information [14].

In principle, another stage of uncertainty results from the bidding process for reserve capacity. Here, we neglect this uncertainty by assuming that the offered reserve capacity is always accepted. For this purpose, we employ average historical price data for the capacity prices. As a result, acceptance is highly likely but we can only gain average revenues for the reserve capacity. In future work, the stochastic formulation could be extended to integrate uncertainty in offered reserve capacity.

2.2. Model extension for stochastic optimization

In this section, we present the model for the provision of control reserve by an integrated batch production and utility system. Due to the space limitations, we only present the changes of the model from the integrated scheduling without control reserve provision. Our method determines the production schedule, the operation of the utility system if control reserve is requested or not requested, the offered reserve capacity and the offered energy price. Inputs are the product demand of the production system, the gas price, the spot-market price for electricity, average capacity price for control reserve provision and the probability of control-reserve request. We formulate a stochastic programming model as MILP.

Control-reserve capacity is offered as indivisible. Offering indivisible control-reserve capacity is possible in some control-reserve markets. In this case, the control-reserve provider avoids the delivery of

control reserve between the offered reserve capacity and zero reserve capacity. Thus, the model only needs to ensure the delivery of the offered reserve capacity. Furthermore, control-reserve capacity is only offered in integer values which is mandatory for some offers in control-reserve markets, e.g., for offers below $5\,\mathrm{MW}$ in Germany.
In the following equations, we write variables in capital and italic letters. Parameters are written in non-italic and small letters.

Objective Function

The model's objective is to minimize the cost for operating the utility system and the production system C^{total}. The objective function considers five cost terms:

$$\min C^{total} = \sum_{t \in T} (C_t^P + C_t^{EL} - R_t^{EL} + C_t^{Gas,NO} - R_t^{R,tot}). \tag{1}$$

C_t^P describes the cost for operating the production system. C_t^{EL} are the cost for buying electricity from the grid. R_t^{EL} defines the revenue that is generated when selling electricity to the grid. $C_t^{Gas,NO}$ describes the cost for buying gas from the grid in the case no control reserve is requested. The gas cost when control reserve is requested are considered in $R_t^{R,tot}$, where $R_t^{R,tot}$ describes the revenue for providing control reserve. The electricity cost is not changed if control reserve is requested. Thus, by request of control reserve, only the gas cost are changed. By minimizing these five cost terms, the cost for operating the overall system are minimized.
The constraints for the stochastics are described in more detail in the following. Here, we provide the equations for the participation in the control-reserve market, which are the extension of the integrated scheduling problem. A detailed version of the integrated scheduling problem without the provision of control reserve is stated in Leenders et al. [11].

Revenues of participating in the control-reserve market

In the objective (Eq. (1)), the total revenues for providing control reserve $R_t^{R,tot}$ are considered. The total revenues for providing control reserve $R_t^{R,tot}$ are the sum of revenues from positive and negative control reserve. The revenues from positive $(cr = POS)$ and negative $(cr = NEG)$ control reserve $R_{t,cr,ep}^R$ have three terms in every time step t, i.e. the first stage variable: (a) revenues for providing control-reserve capacity, and the second stage variables: (b) the extra cost for gas if control reserve is delivered and (c) revenues from delivering control-reserve energy:

$$\begin{aligned} R_{t,cr,ep}^R = & \overbrace{P_{t,cr}^{RP} \cdot \mathrm{p}_{t,cr}^{CAP}}^{(a)} + \overbrace{\omega_{t,cr,ep} \cdot (C_t^{Gas,NO} - C_{t,cr}^{Gas})}^{(b)} \\ & + \overbrace{P_{t,cr}^{RP} \cdot \mathrm{ep}_{t,cr,ep}^R \cdot \omega_{t,cr,ep}}^{(c)} \quad \forall t \in T, cr \in CR, ep \in EP_{cr}. \end{aligned} \tag{2}$$

The revenues for providing control-reserve capacity (a) are determined by the amount of control-reserve capacity $P_{t,cr}^{RP}$ and the capacity price $\mathrm{p}_{t,cr}^{CAP}$. These revenues are paid even if no control-reserve energy is requested and, thus, are not multiplied with the probability for control-reserve request. The extra cost for gas (b) if control reserve is delivered are determined with the probability for control-reserve request $\omega_{t,cr,ep}$ and the difference between the gas cost if control reserve is requested $C_{t,cr}^{Gas}$ and if no control reserve is requested $C_t^{Gas,NO}$. The extra cost for gas are caused by different operation of the utility system to provide a different amount of electricity to the grid and can be negative.
The revenues from delivering control-reserve energy (c) are determined by the amount of control-reserve capacity $P_{t,cr}^{RP}$, the energy price $\mathrm{ep}_{t,cr,ep}^R$ and the probability for control-reserve request $\omega_{t,cr,ep}$. In reality, the energy price is a continuous variable and the probability of request is a non-linear function of the energy price. The higher the energy price, the lower the probability of request and

vice versa. Furthermore, the energy price is multiplied with the offered reserve capacity, which is a integer variable. To obtain a MILP model, we linearize the term (c). For this purpose, we discretize the energy price as parameter $\mathrm{ep}^{R}_{t,cr,ep}$, where the index ep distinguishes the discrete energy prices. Consequently, for each discrete energy price we obtain the probability of request as parameter $\omega_{t,cr,ep}$. At the control-reserve market, only a single energy price can be offered for negative and positive control reserve each. Eq. (3) ensures that only a single combination of positive energy prices ep^{+} and negative energy prices ep^{-} is chosen. Thus, the binary variable $\lambda_{t,ep^{+},ep^{-}}$ equals 1 for the chosen energy prices in every time step t:

$$\sum_{ep^{+}\in EP^{+}} \sum_{ep^{-}\in EP^{-}} \lambda_{t,ep^{+},ep^{-}} = 1 \quad \forall t \in T. \tag{3}$$

The total revenues for providing control reserve $R^{R,tot}_{t}$ are than determined by:

$$R^{R,tot}_{t} = \sum_{ep^{+}\in EP^{+}} \sum_{ep^{-}\in EP^{-}} (R^{R}_{t,POS,ep^{+}} + R^{R}_{t,NEG,ep^{-}}) \cdot \lambda_{t,ep^{+},ep^{-}} \quad \forall t \in T. \tag{4}$$

The multiplication of $R^{R,tot}_{t}$ and $\lambda_{t,ep^{+},ep^{-}}$ would result in a MINLP. We linearize Eq. (4) by a Big-M reformulation:

$$R^{R,tot}_{t} \leq R^{R}_{t,POS,ep^{+}} + R^{R}_{t,NEG,ep^{-}} + \mathrm{M} \cdot (1 - \lambda_{t,ep^{+},ep^{-}}) \quad \forall t \in T, ep^{+} \in EP^{+}, ep^{-} \in EP^{-}. \tag{5}$$

Eq. 5 considers the revenues for positive control reserve $R^{R}_{t,POS,ep^{+}}$ and negative control reserve $R^{R}_{t,NEG,ep^{-}}$. The binary variable $\lambda_{t,ep^{+},ep^{-}}$ chooses the energy price for positive and negative control reserve. M is a sufficiently large number. The revenues of participating in the control-reserve market $R^{R,tot}_{t}$ are maximized by the objective function. Thus, Eq. (4) can be replaced by the linearization in Eq. (5).

Because, in many control-reserve markets, control reserve has to be offered for a certain time slice, the amount of control-reserve capacity provided $P^{RP}_{t,cr}$ needs to be equal in each time slice:

$$P^{RP}_{t,cr} = P^{RP}_{t+a,cr} \quad \forall t \in \{1, 1 + \mathrm{t}^{\mathrm{s}}, \ldots, 1 + \mathrm{t}^{\mathrm{h}} - \mathrm{t}^{\mathrm{s}}\}, a \in \{1, 2, \ldots, \mathrm{t}^{\mathrm{s}} - 1\}, cr \in CR. \tag{6}$$

t^{h} is the time horizon considered for scheduling the production and utility system. t^{s} is the length of each time slice. Also the energy price needs to be be equal in each time slice t^{s} and, thus, the binary variable $\lambda_{t,ep^{+},ep^{-}}$ is equal:

$$\begin{aligned} \lambda_{t,ep^{+},ep^{-}} = \lambda_{t+a,ep^{+},ep^{-}} \; \forall t \in \{1, 1 + \mathrm{t}^{\mathrm{s}}, \ldots, 1 + \mathrm{t}^{\mathrm{h}} - \mathrm{t}^{\mathrm{s}}\}, a \in \{1, 2, \ldots, \mathrm{t}^{\mathrm{s}} - 1\}, \\ ep^{+} \in EP^{+}, ep^{-} \in EP^{-}. \end{aligned} \tag{7}$$

Energy Balances

The energy balance couples the production system with the utility system, i.e., the energy demand of the production system has to be fulfilled by the utility system. In order to ensure that the utility system is able to provide the requested control reserve, the energy balances have to be defined for every scenario. Again, the three scenarios $cr = \{NO, POS, NEG\}$ are distinguished. Eq. (8) gives the energy balance for electricity for the three scenarios considering the electricity consumption on the left side and the electricity production on the right side:

$$\begin{aligned} D^{el}_{t} + \alpha_{cr} \cdot P^{RP}_{t,cr} + \sum_{cu\in CU} P^{UU}_{t,cu,cr} + P^{-,EL}_{t} = & P^{+,EL}_{t} + \sum_{pu\in PU} P^{UU}_{t,pu,cr} \\ & \forall t \in T, cr \in \{POS, NEG, NO\}. \end{aligned} \tag{8}$$

The electricity balance considers the following variables: as first-stage variables: the electricity demand from the batch production system D_t^{el}, the amount of control reserve provided $P_{t,cr}^{RP}$, the electricity $P_t^{-,EL}$ sold to the grid and the electricity purchased from the grid $P_t^{+,EL}$, and as second-stage variables: the power consumption $P_{t,cu,cr}^{UU}$ of the utility units consuming electricity, e.g., compression chillers or electric boilers, and the electrical power generation $P_{t,pu,cr}^{UU}$ of the utility units producing electricity, e.g., combined-heat-and-power engines. The parameter α_{cr} distinguishes the three scenarios and is 0 in the scenario 'no control reserve is requested' (NO), 1 in the 'scenario positive is requested' (POS), or (-1) in the scenario 'negative control reserve is requested' (NEG).
By the request of control reserve, the energy demand and at the same time the production schedule of the production system are not affected . Thus, we consider that only the utility system provides the request of control reserve. Furthermore, our method allows that control reserve could be requested in every time step. If control reserve is requested, the utility system just operates a different set of utility units to provide control reserve and, still, supplies the same energy to the production system. Therefore, our method ensures security of energy supply no matter at which time and how long the offered control reserve is requested.

3. Case-Study

The proposed method is applied to a case study with the batch production system model from Kondili et al. [15] and the utility system model from Baumgärtner et al. [16]

3.1. Description of the case study

The integrated batch production and utility system is assumed to participate in the German tertiary control-reserve market [13]. In the German tertiary control-reserve market, offers can only be given as integer values if the offered control-reserve capacity is below $5\,\mathrm{MW}$. Furthermore, offers can be declared as indivisible. Indivisible offers are only fully requested, where other offers can be requested partly. Here, we consider indivisible offers of control-reserve capacities between $0\,\mathrm{MW}$ and $5\,\mathrm{MW}$. In Germany, tertiary control reserve is traded for $4\,\mathrm{h}$ time slices. If tertiary control reserve is requested, the control reserve needs to be provided within $15\,\mathrm{min}$. We assume that this requirement is fulfilled by the modeled utility units.

In our case study, we model a day from 2018 for the capacity price and use historical data from the German tertiary reserve market. In our method, we discretized the energy price. From the historical data and for each time slice, we obtain 4 energy prices for positive and negative control reserve each. We derive a probability of request for every time slice. The probability of request is derived from historical data based on [13; 17]. For each considered energy price, we analyze how often and how long reserve capacity was requested in one year. The probability of request is then defined as the number of time steps in which reserve capacity was requested for the energy price divided by all analyzed

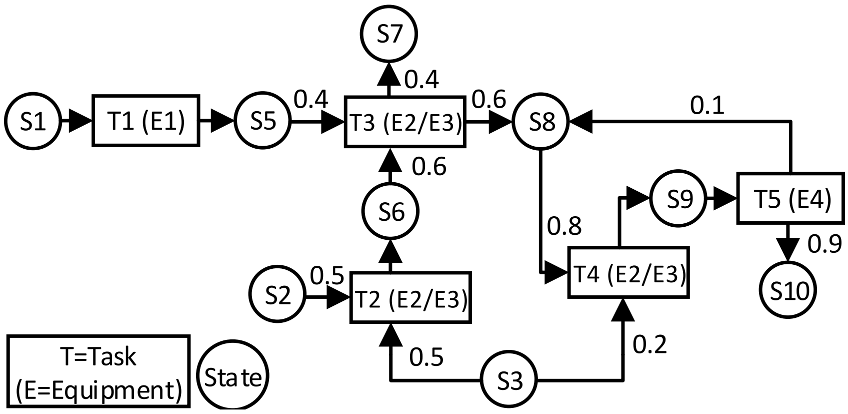

Figure 3: Batch production system of the case study from Kondili et al. [15]. For each task, we added demands of low- and high-temperature heating, cooling and electricity.

time steps. The electricity price for selling electricity is taken for each hour from the spot market price. The average selling price is 39 €/MWh and for the average purchasing price we increased this price by 9.4 €/MWh.
For the batch production system, we added demands for low- and high-temperature heating, cooling and electricity for each task. We schedule the systems for a 24 h time horizon with a time step length of 1 h. The product demand to be fulfilled is 224 t of S07 and 432 t of S10. The equipment in the batch production system can process the following maximum batch size: E01 (80 t), E02 (90 t), E03 (70 t), E04 (70 t). The utility system has the following units and corresponding thermal capacity: 3 gas-driven boilers (2 MW, 1.5 MW, 0.5 MW), 3 electricity-driven boiler (2 MW, 1.5 MW, 0.5 MW), 3 compression chillers (2.5 MW, 1.5 MW, 0.5 MW), 3 absorption chillers (2.5 MW, 1.5 MW, 0.5 MW), 4 gas-driven combined-heat-and-power engines (3 MW, 2.5 MW, 2 MW, 1.5 MW). Thus, the utility system consumes gas and can purchase or sell electricity to provide the production system with heat, cold and electricity.
The optimization models are formulated in GAMS 27.3.0 [18] and solved by ODH 4.2.6 with CPLEX 12.9.0.0 [19]. The time limit is set to 7200 s with an optimality gap of 0.1 %. We compare our method with a sequential scheduling with and without providing control reserve and an integrated scheduling without providing control reserve.

3.2. Results

In the case study, the proposed method reaches cost savings of 4.63 % compared to the sequential scheduling without control reserve (Figure 4). Furthermore, the method saves 3.30 % compared to sequential scheduling with control-reserve provision and 2.33 % compared to integrated scheduling without control reserve.
In the proposed method, provision of control reserve is chosen in every time slice. But in some time slices not both positive and negative control reserve are chosen. The chosen negative control-reserve capacity is the maximum of 5 MW from 0-20 h and 1 MW from 20-24 h. The chosen positive control-reserve capacity is the maximum of 5 MW from 0-8 h, 3 MW from 8-12 h, 4 MW from 16-20 h and 1 MW from 20-24 h. From 12-16 h, no positive control reserve is chosen. For negative and positive control reserve, different energy prices are chosen from the discretized energy prices. The chosen energy prices range from the lowest to the highest discretized energy prices. The different energy prices change the probability of request. Thus, by optimizing the energy price and the amount of control reserve provided, a trade-off is resolved: A higher energy price leads to a lower probability of request. The probability of request is not only a weighting factor for potential revenues from control reserve, but also weights the potential additional cost of changing the schedule of the utility system when control reserve is requested. Consequently, our method optimizes the schedule of both systems

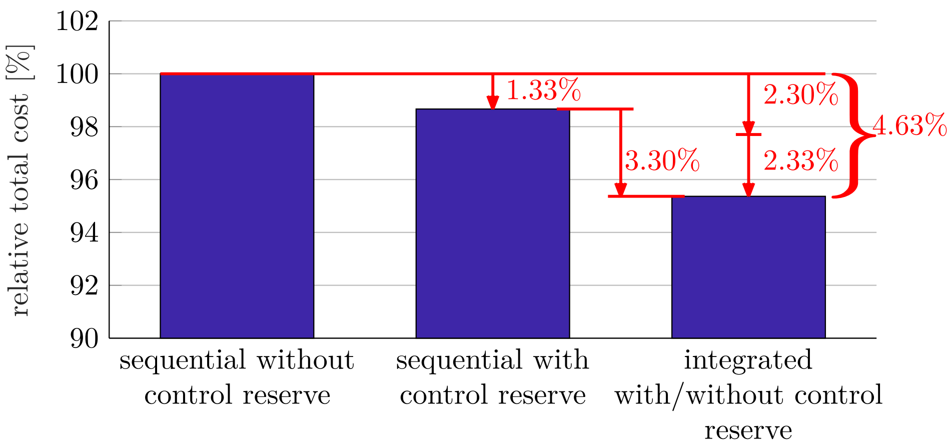

Figure 4: Relative total cost for production and utility system for sequential scheduling and integrated scheduling. Both approaches are applied with and without the possibility to provide control reserve.

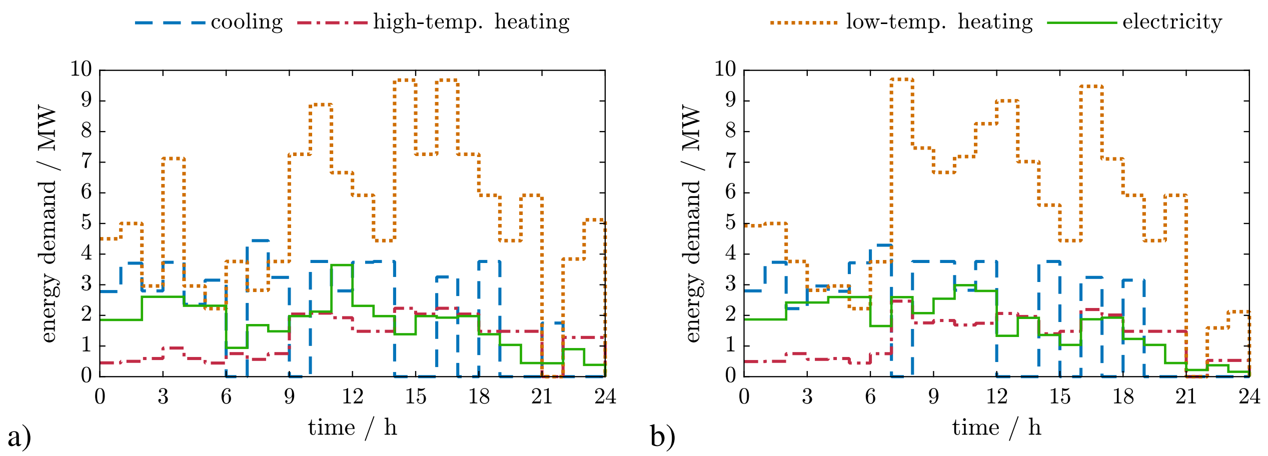

Figure 5: Energy demand of the production system for the integrated scheduling without (a) and with (b) provision of control reserve. temp.=temperature

simultaneously such that the highest expected revenues are gained from the trade-off (Figure 4).
If we compare the cost savings by providing control reserve isolated for sequential and integrated scheduling, participating in the control-reserve market is more beneficial in the integrated scheduling than in the sequential scheduling: Cost savings in the integrated scheduling are $2.33\,\%$ compared to $1.33\,\%$ in the sequential scheduling.
The sequential scheduling is solved to optimality with consideration of control reserve in $995\,\mathrm{s}$ and without consideration of control reserve in $966\,\mathrm{s}$. In both sequential optimizations, the optimization of the utility system is fast (below $40\,\mathrm{s}$) and the scheduling of the production system takes $960\,\mathrm{s}$. In the integrated scheduling without providing control reserve, a gap of $0.5\,\%$ is reached within the time limit. In our method for the integrated scheduling with providing control reserve, a gap of $4.9\,\%$ remains. We also performed the integrated scheduling with an increased time limit of $24\,\mathrm{h}$ time limit, but still the gap remained high at $3.7\,\%$. Nevertheless, our method finds a solution with lower cost compared to the best benchmark already within $188\,\mathrm{s}$.
The energy demands are different in the integrated scheduling without and with provision of control reserve (Figure 5). As stated in Section 2., the energy demand of the production system remains unchanged if control reserve is requested. The peaks in the energy demand differ not significantly between the integrated scheduling without and with provision of control reserve. Thus, the energy demand is only shifted. This shifting of the energy demand is most significant in the demand of low-temperature heating. Still, the shift in energy demand is non-trivial and could not have been identified by simple heuristics.
The amount of energy provided by the different types of utility units differ between the scheduling methods. If control reserve is provided in the integrated scheduling, the combined-heat-and-power units provide on average only $69\,\%$ of the heat compared to $78\,\%$ if no provision of control reserve is considered (Figure 6). The gas-driven boilers increase their share of provided heat from $22\,\%$ to $28\,\%$ if control reserve is provided. A single electricity-driven boiler is operated in only 1 time step if no control reserve is provided. The electricity-driven boiler provide $4\,\%$ of the heat demand if control reserve is provided. Thus, a higher variety of operated utility units enables the provision of control reserve.
If positive control reserve is requested, the combined-heat-and-power units increase their share of heat supply from $65\,\%$ to $84\,\%$ (Figure 6 (c)). Additionally, the gas-driven boilers decrease their share of heat supply and the electricity-driven boilers are idle.
If negative control reserve is requested, the combined-heat-and-power units decrease their share of heat supply to $33\,\%$ (Figure 6 (d)). At the same time, the gas-driven boilers and the electricity-driven boilers increase their share of heat supply to $40\,\%$ and $27\,\%$, respectively. From $21\,\mathrm{h}$ to $22\,\mathrm{h}$, the production system has no heat demand but requires cold and electricity in both integrated scheduling with and without provision of control reserve. The utility system provides the cooling demand only

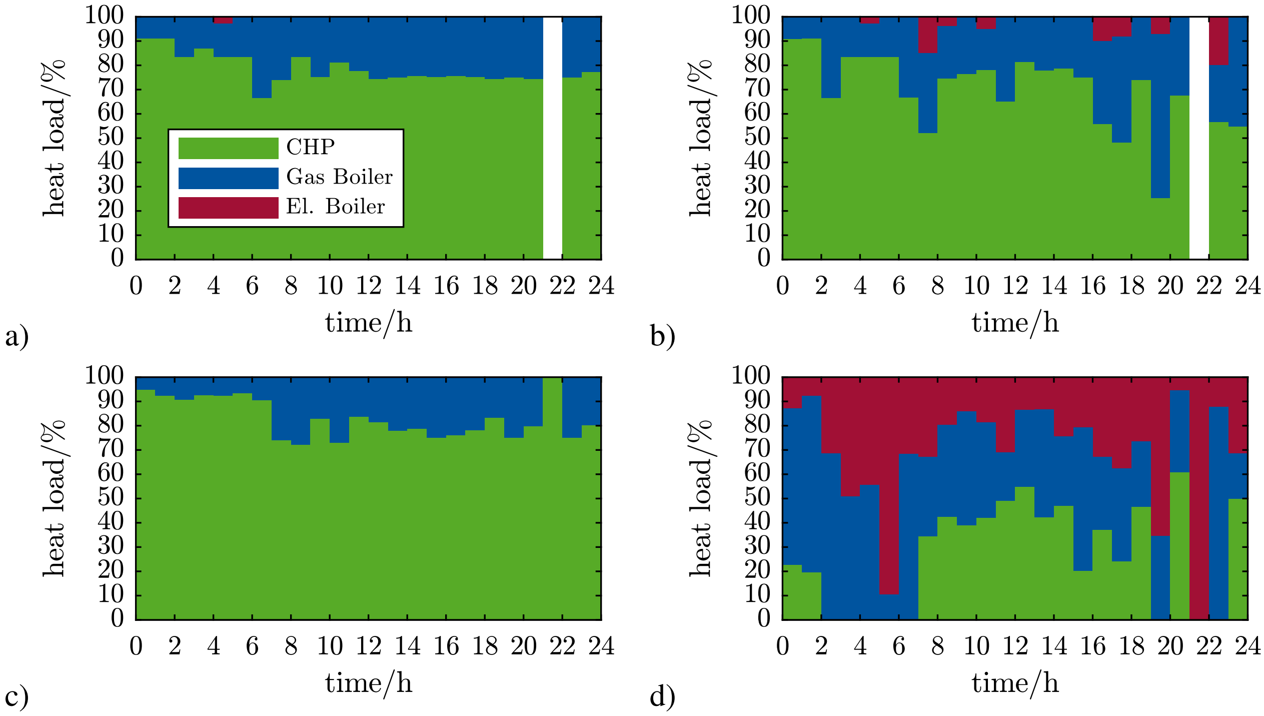

Figure 6: Share of heat supply by the utility units for the integrated scheduling without (a) and with (b) provision of control reserve if no control reserve is requested. Furthermore, the share of heat supply by the utility units is given if only positive control reserve (c) and only negative control reserve (d) is requested. The actual operation is a mix of (b), (c) and (d), depending on the actual control reserve requested. El.=Electricity-driven

with compression chillers if no control reserve is requested. If positive control reserve is requested, the cooling demand is partly supplied by an absorption chiller. The heat to run the absorption chiller is then supplied by an combined-heat-and-power engine, which also provides the requested positive control reserve. In the same way, if negative control reserve is requested, the absorption chiller is supplied by an electricity-driven boiler, which then supplies the negative control reserve. From $12\,\mathrm{h}$ to $16\,\mathrm{h}$, no positive control reserve is provided. Thus, the operation of the utility system is equal to if no control reserve is requested in these time steps (Figure 6). Concluding, control reserve is provided by changing the operation of all utility units. Furthermore, the optimal operation of the utility system is even different without and with provision of control reserve if no control reserve is requested.

4. Conclusions

A method is proposed for an integrated scheduling of batch production and utility system for control-reserve provision. The method optimizes the production schedule and, consequently, its energy demand for provision of control reserve by the utility system. The method optimizes the offered amount of negative and positive control reserve in control-reserve markets. In our method, we consider the probability of being requested and the expected revenues from providing requested control reserve. Furthermore, the method provides the schedule of the utility system system if control reserve is requested. The method considers an average capacity price and, thus, no uncertainty for accepting the offered capacity price.

The method is applied to a case study and shows high cost savings compared to the sequential scheduling with control-reserve provision ($3.30\,\%$) and integrated scheduling without control-reserve provision ($2.33\,\%$). The optimization model did not reach the optimality gap in the given time limit, but the best solution is found rapidly and already outperforms the other approaches. Thus, the method enables production and utility system operators to schedule integrated systems for an increasing participation in energy markets.

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