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An adaptive discretization MINLP algorithm for optimal synthesis of decentralized energy supply systems☆

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ABSTRACT

Decentralized energy supply systems (DESS) are highly integrated and complex systems designed to meet time-varying energy demands, e.g., heating, cooling, and electricity. The synthesis problem of DESS addresses combining various types of energy conversion units, choosing their sizing and operations to maximize an objective function, e.g., the net present value. In practice, investment costs and part-load performances are nonlinear. Thus, this optimization problem can be modeled as a nonconvex mixed-integer nonlinear programming (MINLP) problem. We present an adaptive discretization algorithm to solve such synthesis problems containing an iterative interaction between mixed-integer linear programs (MIPs) and nonlinear programs (NLPs). The proposed algorithm outperforms state-of-the-art MINLP solvers as well as linearization approaches with regard to solution quality and computation times on a test set obtained from real industrial data, which we made available online.

1. Introduction

We propose an adaptive discretization algorithm for the superstructure-based synthesis of decentralized energy supply systems (DESS). The proposed optimization-based algorithm employs discretization of the continuous decision variables. The discretization is iteratively adapted and used to obtain valid nonconvex mixed-integer nonlinear program (MINLP) solutions within short solution time.

DESS can consist of several energy conversion components (e.g., boilers and chillers) providing different utilities (e.g., heating, cooling, electricity). DESS are highly integrated and complex systems due to the integration of different forms of energy and their connection to the gas and electricity market as well as to the energy consumers. The application of DESS encompasses, e.g., chemical parks (Maréchal and Kalitventzeff, 2003), urban districts (Maréchal et al., 2008; Jennings et al., 2014) and building complexes (Arcuri et al., 2007; Lozano et al., 2009). Energy costs usually match the companies' profits in magnitude (Drumm et al., 2013). Thus, optimally designed decentralized energy supply systems can lead to a considerable increase of profits.

The target of optimal synthesis of DESS is the identification of an (economically) optimal structure (which types of equipment and how many units?) and optimal sizing (how big?), while simultaneously considering the optimal operation of the selected components (which components are operated at which level at what time?) (Frangopoulos et al., 2002). These three decision levels could be considered sequentially. However, the levels influence each other, thus only a simultaneous optimization will find a global optimal solution. In this paper, we consider the simultaneous optimization using superstructure-based synthesis. A superstructure needs to be predefined and consists of a superset of possible components, which can be selected within the synthesis of the DESS. If the superstructure is chosen too small, optimal solutions could be excluded, if the superstructure is chosen too large, computational effort become prohibitive. Therefore some of the authors proposed a successive superstructure expansion algorithm (Voll et al., 2013b).

The synthesis of DESS contains binary decisions for the selection of energy conversion components as well as the on/off status in the operation of each component. Combined with nonlinear part-load performance of the energy conversion components, nonlinear economy-of-scale effects in the investment cost curves and strict

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energy balances, the synthesis of DESS leads in general to a nonconvex MINLP (Bruno et al., 1998). Typically, an economic objective function is considered, e.g., the net present value is maximized or the total annualized costs are minimized, furthermore also ecologic objective functions can be considered (Østergaard, 2009).

Metaheuristic optimization approaches have been proposed for the synthesis of DESS: evolutionary algorithms were proposed for superstructure-free linearized synthesis as well as superstructure-based MINLP synthesis (Dimopoulos and Frangopoulos, 2008; Voll et al., 2012). Stojiljkovic et al. (2014) proposed a heuristic for structural decisions and solved an mixed-integer linear program (MILP) for operation decision. These heuristic approaches do not provide any measure of optimality.

To allow rigorous optimization, mostly linearized approaches are considered for synthesis of practically relevant problems. In the resulting MILPs, the nonlinearities are approximated by piecewise-linearized functions. First, Papoulias and Grossmann (1983) linearized the investment cost functions, the nonlinear operation conditions are modeled as discrete, but fixed operation conditions. Continuous operation decision with constant efficiency is addressed by Lozano et al. (2009) for MILP synthesis of energy supply systems in the building sector using fixed capacities. Voll et al. (2013b) proposed an MILP model accounting for piecewise-linearized part-load dependent operation conditions and piecewise-linearized investment costs for continuous component sizing. Recently, Yokoyama et al. (2015) modeled the structure decision with integer variables for the type and discrete sizes of components, thus, modeling the nonlinear investment cost curve is not required. The operation power is modeled as linear function within allowed operation ranges.

The solution of the linearization approaches only results in approximated solutions. However, solving the MINLP of superstructure-based synthesis is computationally demanding. First, an MINLP model for the operation of DESS was considered by Prokopakis and Maroulis (1996). The model takes into account the nonlinear size- and load-dependent components performance. Papalexandri et al. (1998) and Bruno et al. (1998) generalized the MINLP formulation to the optimal synthesis of DESS. Due to the complexity of the problem, only one component of each type is considered in the superstructure and the demand is considered by a single load case. An MINLP model considering multiple, detailed components as well as multiple load cases for the demand profile have been proposed by Varbanov et al. (2004, 2005). To solve the resulting large MINLP, nonlinearities of part-load performance are predefined in an iterative loop and internally MILPs are solved. Chen and Lin (2011) solved an MINLP for a steam-generation plant, the nonlinearities of part-load performance are optimized, nevertheless the model considers steam as a single demand type. The problem of integrated optimization of DESS and process system commonly results in large-scale MINLPs. Recently Zhao et al. (2015) decomposed the integrated MINLP of optimal operation of DESS and process system into an MILP and NLP problem and the variables are exchanged between both problems. Moreover, Tong et al. (2015) proposed a discretization approach for the MINLP of optimal operation of DESS and process system. Further discretization approaches for solving nonconvex MINLP problems with different practical applications are discussed in Section 3.

In this paper, MINLP solutions are obtained by an adaptive discretization algorithm for the nonlinear synthesis problem of DESS. (Commercial) MINLP solvers such as BARON (Tawarmalani and Sahinidis, 2005) reach computational limits for relative small test cases of the considered MINLP, accounting for nonlinear investment cost and multivariate nonlinear part-load dependent operation performance. We developed a problem-tailored adaptive discretization algorithm to obtain valid solutions of the MINLP within short solution time. The algorithm discretizes the continuous component size within bounds given by practically available component size limits. The whole range of size can be selected for each type of component, since the discretization is iteratively adapted. Thus, the algorithm does not require predefining discrete sizes of the components in the superstructure. Moreover, the operation of each component for each load case is discretized with finer steps depending on the part-load performance of each type of energy conversion component. Thus, various energy conversion components with different capacities and with corresponding investment and maintenance costs can be selected and adjusted to meet the energy demands in each load case.

We state our MINLP model of the DESS in Section 2. In Section 3, we describe the proposed adaptive discretization algorithm. In Section 4, we apply the algorithm to a test set of a real-world example. Solutions and performance are compared to a standard MINLP solver as well as state-of-the-art linearization approaches with MILP models.

2. Optimization models for decentralized energy supply systems

In this section, we present an MINLP model for optimal synthesis of DESS (Section 2.2) as well as a piecewise-linearized model (Section 2.3), which we use as benchmark for our adaptive discretization algorithm. First of all, in Section 2.1, notations of parameters, decisions, and the optimization problem as a whole are given.

2.1. Equipment, parameters, and decisions

The set of energy conversion units, which can be set up to meet the demands, is denoted by superstructure $S = B, \dot{\cup} C \dot{\cup} T \dot{\cup} A$ and encompasses a set of boilers B, a set of combined heat and power engines C, a set of turbo-driven compressor chillers T and a set of absorption chillers A (Fig. 1). Further equipment could be included, but we focus here on the problem introduced in our earlier work (Voll et al., 2013b). All units $s \in S$ in the superstructure are not further specified than their type of equipment. Note, that an optimal DESS is likely to contain multiple units of one type which is in strong contrast to classical process synthesis problems (Farkas et al., 2005).

The set of load cases considered for the operation of the DESS is denoted by L. The length of load case $\ell \in L$ is denoted by $\Delta_\ell \geq 0$. Furthermore, $\dot{E}_\ell^{\text{heat}} \geq 0$, $\dot{E}_\ell^{\text{cool}} \geq 0$, and $\dot{E}_\ell^{\text{el}} \geq 0$ denote the demands of heating, cooling, and electricity, which have to be satisfied with equality by the DESS in every load case $\ell \in L$. For each unit $s \in S$, its continuous size $\dot{V}_s^{\text{N}}$ has to be determined. The size $\dot{V}_s^{\text{N}}$ specifies the maximum (nominal) output energy and has to be between a minimum size $\dot{V}_s^{\text{N,min}}$ and a maximum size $\dot{V}_s^{\text{N,max}}$. For combined heat and power (CHP) engines, the output is not unique (heat and electricity). In this case, the size refers to the maximum heat output. The investment cost of unit $s \in S$ depends on its size $\dot{V}_s^{\text{N}}$ and is given by the nonlinear function $I_s(\dot{V}_s^{\text{N}})$. Further, maintenance costs are considered as constant factors m_s in terms of investment costs.

The output power of unit $s \in S$ at load case $\ell \in L$ is to be determined and is denoted by $\dot{V}_{s\ell}$. Again, for CHP, the output power refers to the heat output. The nonlinear function $\dot{V}_{s\ell}^{\text{el}}(\dot{V}_{s\ell}, \dot{V}_s^{\text{N}})$ describes the electricity output of a CHP $s \in C \subseteq S$. For each unit $s \in S$ operated in load case $\ell \in L$, a minimum part-load operation is required. Thus, the condition $\alpha_s^{\min} \dot{V}_s^{\text{N}} \leq \dot{V}_{s\ell} \leq \dot{V}_s^{\text{N}}$ with minimum part-load factor $0 \leq \alpha_s^{\min} \leq 1$ has to hold. If $s \in S$ is not operated in load case $\ell \in L$, we set $\dot{V}_{s\ell} = 0$. The input needed to generate the output $\dot{V}_{s\ell}$ is described by the nonlinear part-load performance function $\dot{U}_s(\dot{V}_{s\ell}, \dot{V}_s^{\text{N}})$.

Parameters $p^{\text{gas,buy}}$, $p^{\text{el,buy}}$, and $p^{\text{el,sell}}$ denote the purchase price of gas and electricity, and the selling price of electricity from and