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Exploring the Near-Optimal Solution Space for the Synthesis of Distributed Energy Supply Systems

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An optimization-based methodology is proposed for the synthesis of distributed energy supply systems (DESS) exploiting the near-optimal solution space inherent to DESS synthesis problems. The proposed synthesis method generates the optimal solution and a set of promising alternatives, thus providing valuable insight into the synthesis problem and a basis for rational and far-sighted design decisions. For economic optimization, first, single-objective optimization is performed maximizing the net present value. Secondly, integer-cut constraints are employed to automatically and systematically generate structurally different, near-optimal solutions. The methodology is exemplified by a real-world problem from industry, for which retrofit optimization generates a solution that improves the net present value by 39 %. Applying integer-cut constraints reveals a rich near-optimal solution space with many structurally different, but practically equally good solutions: The objective function values of the ten best solution structures lie within a tolerance of 0.17 %.

1. Introduction

Distributed energy supply systems (DESS) are complex systems integrating both centralized units with typically excellent economies of scale and distributed units enabling more efficient operation (Bouffard and Kirschen, 2008). Thus, the synthesis of DESS systems poses non-trivial problems that need to be considered on three, hierarchically-structured levels (Frangopoulos et al., 2002): the synthesis, the design, and the operation level (Figure 1). Moreover, the special characteristics of DESS must be accounted for, i.e., economy of scale of equipment investments, limited capacities of standardized equipment, part-load performance and minimum operation loads of the equipment as well as multiple redundant units (Velasco-Garcia et al., 2011).

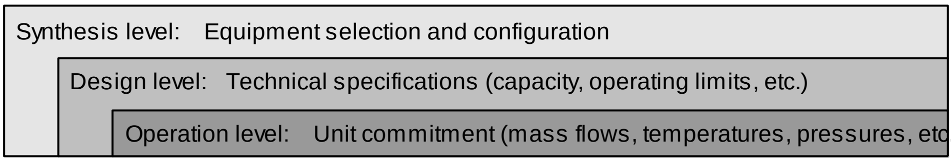

Figure 1. The synthesis task as hierarchically-structured problem on three levels

Recently, the authors proposed a framework for automated optimization-based synthesis of distributed energy supply systems (Voll et al., 2013) that avoids manual superstructure definition. However, the generation of the optimal solution alone is generally insufficient in practice due to the following shortcomings: First, a mathematical model is never a perfect representation of the real world, and thus the optimal solution is usually only an approximation of the optimal real-world solution. Moreover, energy tariffs, energy demands, etc. usually change in the future. However, the optimal solution only reflects the current situation. For these reasons, deeper understanding of the synthesis problem at hand is required to reflect the real-world situation. Thus, this paper focuses on the generation of a set of promising candidate solutions rather than a single optimal solution only. In section 2, the framework for automated optimization-

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based DESS synthesis proposed by Voll et al. (2013) is extended to enable near-optimal solutions generation. In section 3, a real-world industrial synthesis problem is discussed. In section 4, the paper is summarized and conclusions are drawn.

2. Framework for automated optimization-based DESS synthesis

In this section, first, the framework for automated DESS synthesis is briefly presented (section 2.1). In section 2.2, this framework is extended for the automated generation of structurally different, near-optimal solution alternatives.

2.1 Single-objective synthesis approach

The recently proposed framework for automated optimization-based DESS synthesis (Voll et al., 2013) features an algorithm for *superstructure generation* to automatically generate mathematical programming models representing superstructures that incorporate multiple redundant units and topographic constraints (to model on-site constructional limitations): The superstructure generation algorithm is based on the *P-graph* based *maximal structure generation* (MSG) algorithm proposed by Friedler et al. (1992). The MSG algorithm was originally designed for process synthesis, and thus neglects multiple redundant units which are, however, generally necessary for DESS. Instead, superstructures generated by the MSG algorithm incorporate exactly one unit of each technology that can supply the required energy forms. To incorporate multiple redundant units in the superstructure generated by the MSG algorithm, the authors proposed an expansion algorithm, which starts by incorporating a user-specified number of redundant units in the MSG superstructure (if no user-input is provided, the superstructure is assumed to incorporate one unit of each technology). Based on this user-defined superstructure, a *successive algorithm* (Figure 2) is applied that successively employs the superstructure generation algorithm to continuously expand and optimize superstructures incorporating additional units. The successive optimization procedure is performed until optimization of the expanded superstructure models does not yield an improved solution. For details, see Voll et al. (2013). The framework uses a generic component-based modeling, by which arbitrary mathematical programming formulations can be employed. In the present implementation, a robust MILP formulation is used to rigorously optimize the synthesis, design, and operation of distributed energy supply systems accounting for time-varying load profiles, continuous equipment sizing, and part-load dependent operating efficiencies (Yokoyama et al., 2002; Voll et al., 2013).

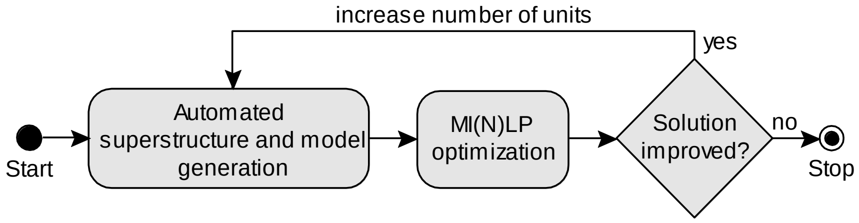

Figure 2. Flow diagram of the successive algorithm for automated superstructure generation and optimization (Voll et al., 2013)

2.2 Generation of near-optimal solution alternatives

In this paper, we propose a synthesis approach that generates structurally different, near-optimal solution alternatives besides the optimal solution, i.e., solutions that differ with respect to the installed equipment. To systematically generate a ranked set of structurally different solutions, in this work, *integer-cut* (IC) constraints (Balas and Jeroslaw, 1972) are applied. In the employed MILP formulation (Voll et al., 2013), the (non-)existence of a piece of equipment *n* is represented by the binary decision variable y_n. For this MILP formulation, the following IC formulation is introduced. Based on the results of *k* already generated solutions, the binary decision variables $y_n^{(k+1)}$ of the next $(k+1)$-th best solution must fulfill the following constraints (1), where $y_n^{(i)}$ represents the decision variable values of the already known i-th best solutions. If these constraints are added to the problem, already identified solutions become infeasible, hence forcing optimization to identify the next best, i.e., the $(k+1)$-th best, solution:

$$\sum_{n=1}^{n_{\max}} \sigma_n \geq 1 \quad \forall i = 1,\ldots,k,$$
$$\text{with } \sigma_n = \begin{cases} y_n^{(i)} - y_n^{(k+1)} & \forall n : y_n^{(i)} = 1, \\ y_n^{(i)} + y_n^{(k+1)} & \forall n : y_n^{(i)} = 0. \end{cases} \tag{1}$$

A more compact form of Eq.(1) has recently been proposed by Fazlollahi et al. (2012). In this work, the compact form of Eq.(1) is used because it directly incorporates the case differentiation in Eq.(1), and thus can be implemented more efficiently. The IC constraints are applied sequentially to automatically generate structurally different, near-optimal solutions: Starting with the optimal solution identified by the successive approach, a series of optimization problems is solved using the successive algorithm (section 2.1), each extended by an IC constraint excluding the already known solutions from consideration. The user can specify the number of solutions to be generated.

3. Practical retrofit problem

In this section, the automated optimization-based synthesis framework is applied to a real-world synthesis problem that is discussed in detail by Voll et al. (2013). The considered energy conversion technologies comprise boilers, CHP engines, compression and absorption chillers. Table 1 lists capacity and cost ranges of the considered technologies as well as their nominal efficiencies and COPs. If available, the necessary parameters are taken from the German market (Gebhardt et al., 2002; Scheunemann and Becker, 2004), or else they were provided by industry partners. A detailed description of the equipment models is given by Voll et al. (2013).

Table 1. Considered energy conversion technologies including their power and cost ranges, and nominal efficiencies η_N (for boilers and CHP engines) and COPs (for chillers)

Technology	Thermal power range / MW	Price range / 10^3 €	η_N, COP_N / -
Boiler	0.1 - 14.0	34 - 380	0.90
CHP engine	0.5 - 3.2	230 - 850	0.87
Absorption chiller	0.1 - 6.5	75 - 520	0.67
Turbo-driven chiller	0.4 - 10.0	89 - 1570	5.54

3.1 Synthesis task

The considered case study is based on a problem from the pharmaceutical industry. The site comprises six building complexes (Figure 3). A public road separates the site into main site (A) and secondary site (B). On site A, all building complexes are connected via a central heating and cooling network. In the base case scenario, site B is not connected to the cooling, but only to the heating network. Furthermore, in base case, the production process on site B has no demand for cooling, but a new production process is installed inducing cooling demands. However, because of the public road, the installation of an additional pipe connecting site B to the cooling network on site A is not allowed. Both sites are connected to the regional natural gas grid (gas tariff: 6 ct/kWh) and the regional electricity grid (electricity tariff: 16 ct/kWh; feed-in tariff: 10 ct/kWh). Electricity generated on-site by CHP engines can either be used on-site to meet electricity demands or to run compression chillers, or else it can be fed-in to the regional electricity grid. All heat generators must be installed on site A.

The described site has time-varying demands for heating, cooling, and electricity. In this study, monthly-averaged energy demand time series are assumed. Moreover, peak-loads are considered to guarantee adequate equipment sizing. However, the peak-loads occur only during few hours per year, and thus hardly contribute to the annual energy demand. The annual energy demands for electricity, heating, and cooling amount to 47.7 GWh, 28.1 GWh, and 27.3 GWh, respectively.

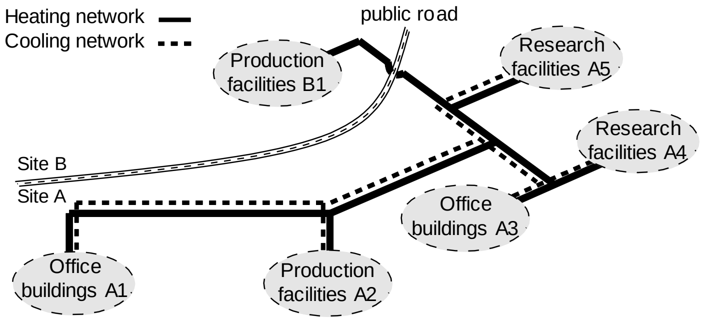

Figure 3. Schematic plant layout. The central heating and cooling network connects five building complexes on site A. The building complex on site B is only connected to the heating network

The existing supply system consists of three boilers, one CHP engine, and three compression chillers. One boiler and one compression chiller require substitution. For the described site, retrofit synthesis is performed taking into account already existing equipment and constructional limitations. For this purpose, the proposed synthesis procedure aims at generating a set of promising solutions rather than a single solution only: As starting point, the optimal solution is identified that maximizes the net present value (NPV). Here, we assume a cash flow time of 10 y and a discount rate of 8 %. Additionally, a ranked set of structurally different, near-optimal solutions is generated. The generated solution set is analyzed to identify both common features and differences among the generated candidate solutions, thus providing deeper understanding of the synthesis problem.

3.2 Economically optimal solution

The NPV-optimal solution incorporates existing as well as new equipment (Figure 4). The NPV adds up to -46.99 M€ (Table 2). The negative NPV is typical for DESS because costs related to installation and operation exceed potential earnings due to electricity feed-in by far. The optimal NPV is an improvement of 39 % compared to the base case configuration, in which the additional cooling demand on site B is not even incorporated yet.

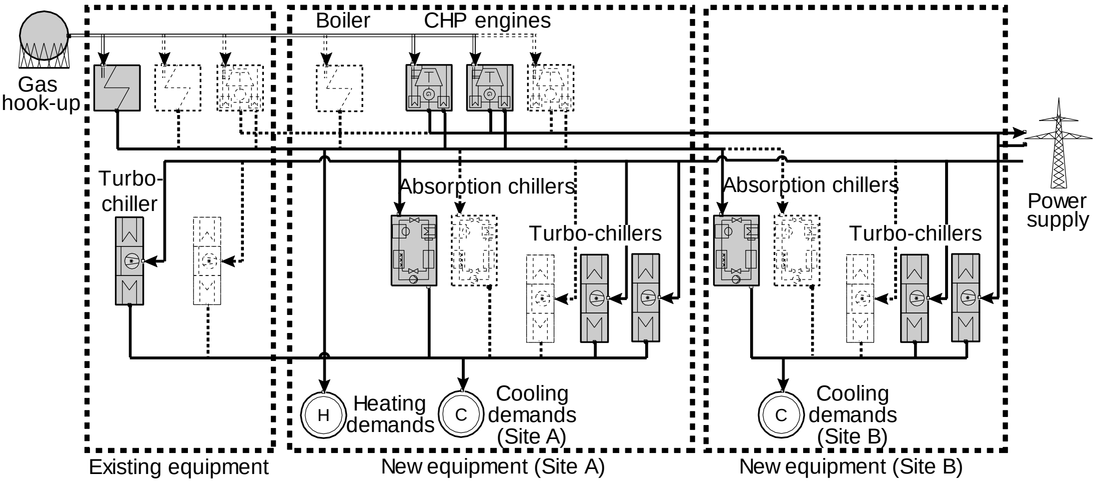

Figure 4. Final superstructure of the successive approach embedding the optimal solution (units highlighted in gray). The electricity demands are not shown in the figure. Spare units (including removed base case equipment) are represented by dashed symbols

In optimal configuration, the heating system consists of one already existing boiler (7.0 MW) and two new CHP engines (each 2.4 MW). The existing boiler is reserved to meet the heating peak-loads in winter. The CHP engines are sized to enable year-round operation at full-load. Cooling on site A is supplied by the existing turbo-chiller (8.0 MW), two new compression chillers (each 1.0 MW), and one new absorption chiller (2.6 MW). The cooling system on site B also encompasses two new compression chillers (0.7 and 0.4 MW) and one new absorption chiller (0.6 MW). All electricity generated by the CHP engines is used on-site for operating the compression chillers and meeting the electricity demand. Installation of redundant units allows for load sharing enabling to run the new equipment close to their maximum efficiencies year-round.

Table 2. Economic parameters of base case and NPV-optimal solution

solution	NPV / M€	investments / M€	energy cost / M€ p.a.	maintenance cost / M€ p.a.
base case	-76.36	0	11.27	0.11
NPV-optimal	-46.99	2.35	6.44	0.22

3.3 Near-optimal solution alternatives

A set of ten solution structures is generated employing the sequential IC approach (section 2.2). A rich near-optimal solution space is identified, in which the objective values of the ten best solutions lie within an optimality gap of 0.17 %. Considering the multitude of additional constraints, uncertainties arising in practice (e.g., cost for equipment installation and control, flexibility towards changing demands, varying energy prices, etc.), and modeling errors, it is practically impossible to make a clear statement about which solutions are better than others strictly based on the NPV. Thus, for rational synthesis decisions, deeper insight is required into the features of the generated solutions. For this purpose, the near-optimal solution alternatives are compared with regard to equipment configuration and sizing: As common feature, the already existing boiler and turbo-chiller remain in all near-optimal solution alternatives (for meeting peak-load demands). Furthermore, all near-optimal solution alternatives incorporate exactly two CHP engines. Besides these common features, the generated solution alternatives differ with respect to the remainder equipment in both configuration and sizing. In the following, prominent solution alternatives are discussed that feature special structural characteristics (Figure 5):

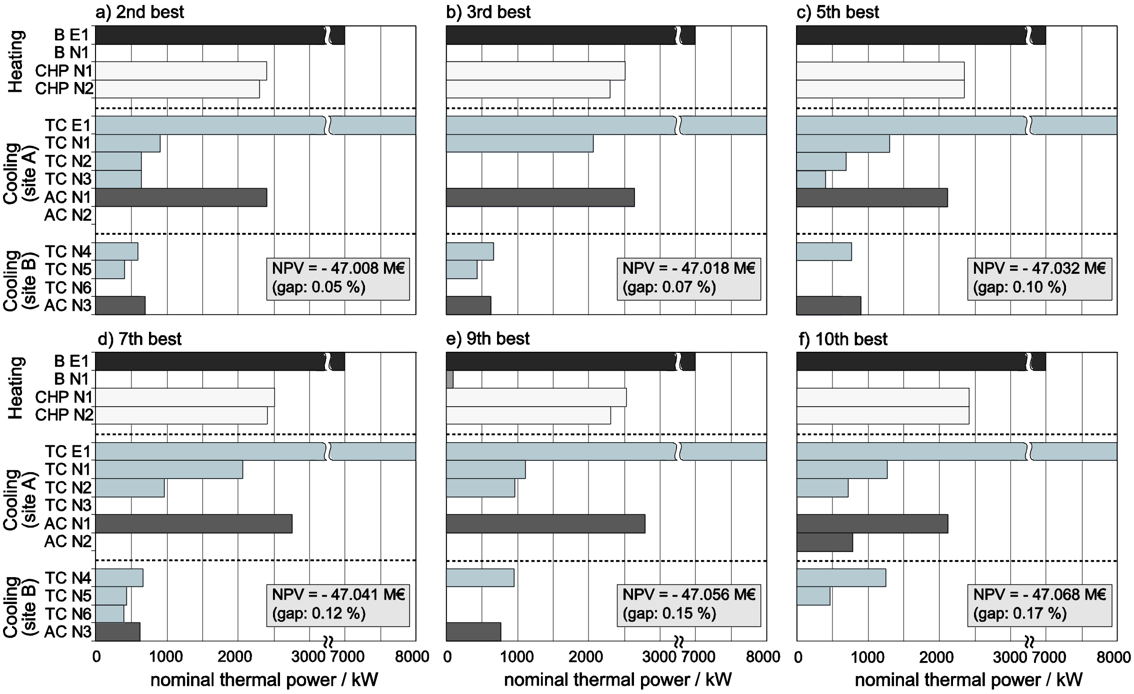

Figure 5. Equipment selection and sizing for six near-optimal solution alternatives: a) 2nd best solution, b) 3rd best solution, c) 5th best solution, d) 7th best solution, e) 9th best solution, f) 10th best solution. The bars represent the technologies' sizing and are filled with different shades of gray for each technology type

- Solutions that incorporate only few units are interesting options because they minimize the complexity of equipment installation and control: E.g., the 3rd best solution contains only two compression and one absorption chiller on site A; the 5th, 9th, and 10th best solutions install only two chillers on site B.
- On the other hand, solutions that incorporate many units are interesting alternatives because they provide greater flexibility with regard to decentralization options, operation strategies, system up- or downscaling, etc.: E.g., the 2nd and 5th best solutions incorporate five chillers on site A; the 7th best solution installs three turbo-chillers on site B; and the 9th best solution installs two boilers.

- Solutions that do not incorporate any absorption chillers on site B avoid costs related to the heating network installation and operation: This is the case, e.g., for the 10th best solution.

3.4 Summary

The presented automated DESS synthesis procedure enables the decision maker to identify and evaluate many options including conventional, cogeneration, and trigeneration concepts taking into account already existing equipment and constructional limitations. Besides the NPV-optimal solution, further near-optimal solution alternatives are generated indicating a rich near-optimal solution space. The generation and analysis of near-optimal solution alternatives supports the design engineer to account for the common features ("must haves") of good solutions as well as for aspects that have not been explicitly considered during optimization, or that might change in the future, such as flexibility with regard to decentralization options, equipment operation, future system up- and downscaling, etc. Thereby, the proposed synthesis approach provides valuable insight into the synthesis problem at hand.

4. Conclusions

In this paper, an automated optimization-based framework is proposed for the synthesis of distributed energy supply systems (DESS) that generates a set of promising solution candidates rather than a single optimal solution only. The framework is based on our algorithm for automated superstructure generation and optimization for single-objective optimization (Voll et al., 2013). The framework is extended to support the generation of near-optimal solution alternatives. The synthesis framework is employed to support the synthesis of a distributed energy supply system in the pharmaceutical industry. First, the synthesis framework is employed to optimize the net present value (NPV). The optimal solution incorporates many redundant units. Second, the framework generates structurally different, near-optimal solution alternatives. It is shown that the synthesis problem features a rich near-optimal solution space with many practically equally-good solutions. Analysis of the generated solutions provides deeper understanding of the synthesis problem than available from the single optimal solution, thus supporting the design engineer to account for aspects that have not been explicitly considered during optimization but that arise in practice. In summary, the proposed framework supports the decision maker to reach rational and far-sighted synthesis decisions through the generation of additional insight into the synthesis problem.

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