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The optimum is not enough: A near-optimal solution paradigm for energy systems synthesis

Philip Voll [a], Mark Jennings [b], Maike Hennen [a], Nilay Shah [b], André Bardow [a, *]

[a] Institute of Technical Thermodynamics, RWTH Aachen University, 52056 Aachen, Germany
[b] Centre for Process Systems Engineering, Department of Chemical Engineering, Imperial College London, London SW 2AZ, United Kingdom

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ABSTRACT

An optimisation-based decision support methodology is presented for the synthesis of energy supply systems on the conceptual level. Previous work in this field has tended to focus on the generation of the single optimal solution. However, given that mathematical models never perfectly represent the real world and that planners are often not aware of all practical constraints, the mathematically optimal solution usually only approximates the real-world optimum, and thus has only limited significance. The presented approach therefore exploits the near-optimal solution space for more rational synthesis decisions. For this purpose, integer-cut constraints are employed to systematically generate a set of near-optimal solutions alongside the optimal solution. In place of the traditional analysis of the single optimal solution, we analyse the generated solution set to identify common features (the "must-haves") and differences (the "real choices") among the good solutions, and features not observed in any of the generated solutions (the "must-avoids"). This approach provides valuable insights into the synthesis problem and opens up a wide range of rational decision options.

The proposed concept is applied to three different real-world problems at the industrial, district, and urban scale. For all three test cases, many near-optimal solutions are identified with different equipment configurations but similar objective function values. Thus, a ranking of the identified solutions strictly based on a single objective value is not productive. Instead, we show that the near-optimal solutions analysis supports the decision process to identify a wider basis of system options, which may be consulted upon to reach rational synthesis decisions.

1. Introduction

Sustainable development [1], as one of the most pressing challenges of today's societies, is closely related to the rational use of energy [2,3]. For this reason, the synthesis of energy-efficient energy systems is considered as one solution strategy for the short- and mid-term [3]. To systematise the synthesis process, exhaustive research has been performed on the development of computer-aided, optimisation-based synthesis methods [4,5]. In this work, we focus on the optimisation-based synthesis of distributed energy supply systems on the conceptual level.

1.1. Distributed energy supply systems

Distributed energy systems (DESS) integrate centralised with distributed (also *decentralised*, or *on-site*) conversion technologies. This is in stark contrast to conventional systems, which generate heat and power in large, centralised units [6]. Integrating many smaller distributed technologies enables to reduce energy losses due to optimal unit operation and on-site power generation [7,8]. Recent studies have drawn out this point, for instance detailing savings in energy available from air-source and ground-source heat pumps [9] or from the charging/discharging profiles of electrical storage [10]. The synthesis of energy-efficient energy systems leads to primary energy savings, CO_2 emissions reductions and can significantly save costs as shown by various authors for building energy systems [11,12], district and urban energy systems [13–18], and industrial energy systems [19–22].

* Corresponding author. Tel.: +49 241 8095380; fax: +49 241 8092255.
E-mail address: andre.bardow@ltt.rwth-aachen.de (A. Bardow).

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Energy systems can be divided into two subsystems: the *energy supply system* (in an industrial context, often referred to as *utility systems* [21,25]) and the *system of final energy users* (Fig. 1). Energy supply systems convert secondary energy into final energy for use in technical processes (final energy users). Final energy users convert the supplied final energy into useful energy and reject heat to the energy supply system. The final energy users represent a variety of users such as residential areas, chemical processes or manufacturing sites. Energy supply systems are linked to the public energy market and the environment. The public energy market supplies secondary energy and takes in feed-in electricity from the supply system. The environment executes heat exchange with the examined system.

1.2. Optimisation-based conceptual synthesis of distributed energy supply systems

In this work, we focus on the synthesis of distributed energy supply systems on the conceptual level [26–29]. The conceptual synthesis usually already fixes a major part of the system's total cost [30,31]. Based on the conceptual synthesis, in the subsequent detailed design stage, all significant process specifics are determined and equipment list and engineering drawings are prepared. The conceptual synthesis of distributed energy supply systems can be addressed on three, hierarchically-structured levels [26]: the synthesis, the design and the operation level (Fig. 2). At the synthesis level, the structure of the energy system is determined, i.e. the selection of the technical components and the optimal layout of their interconnections. At the design level, the units' technical specifications are defined (capacity, operating limits, etc.). Finally, given the system synthesis and design, the optimal operation strategies are specified for each instant of time at the operation level. The system design and operation directly influence the synthesis, and thus, for optimal systems synthesis, all three levels must be taken into account simultaneously, thus posing inherently complex optimisation problems.

Mathematical programming (also *mathematical optimisation* or simply *optimisation*) enables the identification of the optimal solution simultaneously taking into account all modelling details included in the mathematical problem formulation. For this purpose, optimisation algorithms search for the solution that minimises (or maximises) the so-called *objective function*, i.e. the optimisation criterion. During the search for the optimal solution, optimisation algorithms consider the equality and inequality relations, the *constraints*, which represent the system under consideration. According to the three synthesis levels (*synthesis*, *design* and *operation*), the general optimisation problem for distributed energy supply systems is given by a mixed-integer nonlinear programming (MINLP) problem, in which the continuous decision variables represent flow rates, equipment sizing, etc., and the discrete decision variables model the (non-)existence and the on/off-status of energy conversion units [32,33].

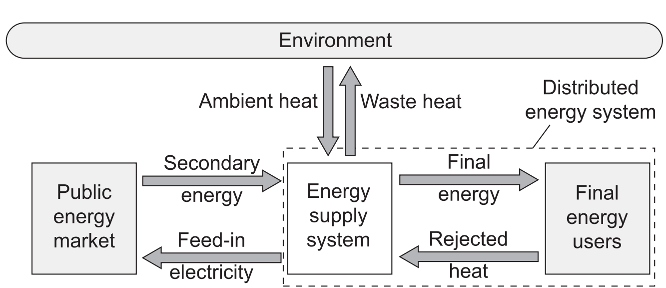

Fig. 1. Energy flows between energy supply systems and neighbouring systems [23,24].

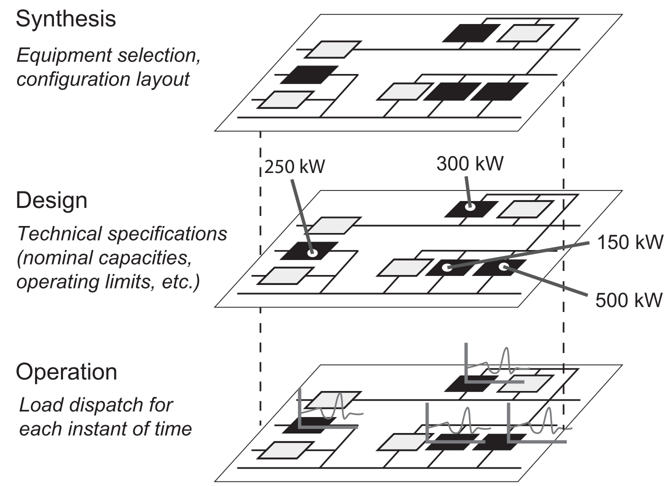

Fig. 2. Hierarchically-structured decision levels for DESS synthesis. An exemplary synthesis problem.

1.3. Limited significance of a single optimal solution

Optimisation-based synthesis methods usually aim at the identification of the single optimal solution that minimises or maximises the objective function. For nonlinear problems, the optimisation problem might suffer from many local optima [34]. However, even a global optimal solution has only limited significance and therefore is generally insufficient in practice due to the following three shortcomings:

i) 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.

ii) The constraints (energy tariffs, energy demands, etc.) are expected to change in the future. However, the optimal solution only reflects the current situation.

iii) The analysis of the single optimal solution provides no information on the solution's robustness, i.e. which parts of the solution are recurring features of good solutions and which parts are rational decision options of possible alternatives that can be modified to respond to practical constraints.

For these reasons, deeper understanding of the synthesis problem is required to reflect the real-world situation. In this paper, we focus on the generation and analysis of a set of promising candidate solutions rather than a single optimal solution only. This approach yields deeper understanding of the synthesis problem, thus offering additional insight into the features of good solutions.

In this study, three real-world problems in the field of energy systems synthesis are considered on an industrial [35], district [14] and urban scale [36]. In the previous publications of these synthesis problems, the analysis focused on the single optimal solutions only. However, in this paper, many near-optimal solutions are observed for all three problems. The analysis of these solutions enables to generate the desired insight into the synthesis task, thus opening up rational decision options. Note that while we consider only single-objective optimisation in this paper, the conclusions of this work apply to multi-objective approaches all the same.

In Section 2, the methodology for the generation and analysis of near-optimal solution alternatives is presented. Next, in Section 3, the three synthesis problems are introduced and analysed with focus on near-optimal solutions generation. The identified