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Multi-objective superstructure-free synthesis and optimization of thermal power plants

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ABSTRACT

The merits of superstructure-free synthesis are demonstrated for bi-objective design of thermal power plants. The design of thermal power plants is complex and thus best solved by optimization. Common optimization methods require specification of a superstructure which becomes a tedious and error-prone task for complex systems. Superstructure specification is avoided by the presented superstructure-free approach, which is shown to successfully solve the design task yielding a high-quality Pareto front of promising structural alternatives. The economic objective function avoids introducing infinite numbers of units (e.g., turbine, reheater and feedwater preheater) as favored by pure thermodynamic optimization. The number of feasible solutions found per number of mutation tries is still high even after many generations but declines after introducing highly-nonlinear cost functions leading to challenging MINLP problems. The identified Pareto-optimal solutions tend to employ more units than found in modern power plants indicating the need for cost functions to reflect current industrial practice. In summary, the multi-objective superstructure-free synthesis framework is a robust approach for very complex problems in the synthesis of thermal power plants.

1. Introduction

One of the central challenges for the world is that of ensuring the rapidly growing energy needs in ways that lead to a prosperous, sustainable and secure energy future [1–3]. The most immediate course ahead is to use existing and new sources of energy more efficiently [4,5]. Cost-effective efficiency improvement of energy systems, especially thermal power plants with large CO_2 emission, is an important contribution in addressing challenges of affordability, sustainability, reliability and security of electricity supply.

Regarding the efficiency improvement of thermal power plants, there have been many traditional measures, e. g., employing additional reheater and feedwater preheaters. More design alternatives can be proposed initially, and then compared and improved by existing analysis methodologies [6–10]. However, the system-level integration of advantageous technologies or concepts has been identified as the new challenge lying ahead. Integration options include topping or bottoming cycles (such as the CO_2-based closed Brayton cycle [11] or the organic Rankine cycle [12]), low-grade waste heat recovery from flue gas [13,14], low-rank coal predrying [15,16] or multiple heat sources (especially solar thermal, [17–20]). Due to the number of technologies to be integrated, the design of a thermal power plant becomes complex. The design of such complex plants requires automatic generation and identification of different system configurations, which is best addressed by mathematical programming, i.e., optimization methods [21–23].

Commonly, the optimal synthesis of energy systems is based on a superstructure [24–28]. A superstructure-based synthesis approach identifies the optimal structure from all structures embedded in a superstructure. The fundamental challenge of superstructure-based optimization is the definition of an appropriate superstructure: On the one hand, good alternatives (in particular, the optimal solution) might be excluded from the superstructure if the superstructure is too small; on the other hand, a large number of meaningless or even infeasible alternatives may be considered [10,29]. To overcome these problems, superstructure-free methods have been proposed [30]. Therein, the solution

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space is not limited *a priori* by a superstructure. However, the solution space has to be properly represented and, more importantly, efficiently explored. With a proper structural representation, it is possible to perform systematic, small and random structural operations on given structures based on certain rules. To perform a stochastic, intelligent and efficient search for optimal solutions, evolutionary algorithms are preferred by modern superstructure-free approaches, e. g., [31–37]. Evolutionary algorithms can apply small and random changes to given structures by the mutation operator. However, these modern superstructure-free approaches are either tailored to specific problems (without sufficient extendability), e. g., heat exchanger network [31,32] and heating-ventilating-air conditioning system [33], or based on a problem-specific structural representation [34] or technology-specific mutation rules [35,36,38] for structural evolution.

To avoid any manual specification of technology-specific mutation rules, a generic superstructure-free framework has been proposed by the authors [30,39] for distributed energy supply systems. In this superstructure-free concept, the considered technologies are classified into a flexible, easy-to-extend energy conversion hierarchy (ECH). Based on this classification, generic mutation rules are formulated that allow the mutation operator to apply changes to the structure without using technology-specific rules. Recently, the ECH and the set of rules was extended by the authors [29] to enable the synthesis of thermal power plants. The extended superstructure-free framework has been evaluated by a simple, exemplary single-objective case study considering the thermal efficiency as the only objective function for the design [29]. In this paper, the extended superstructure-free framework for multi-objective optimal synthesis of thermal power plants is generalized and comprehensively evaluated for a complex bi-objective synthesis problem representing real-world power plants.

The paper is organized as follows: In section 2, the superstructure-free synthesis framework extended in Ref. [29] is generalized for multi-objective synthesis and optimization problems. Then, the superstructure-free synthesis framework is employed and evaluated for complex synthesis problems of thermal power plants by considering the two objective functions, thermal efficiency and cost of electricity, separately and simultaneously (section 3). Finally, the paper is summarized and conclusions are drawn (section 4).

2. Multi-objective superstructure-free optimization-based synthesis framework

The general multi-objective optimization-based synthesis problem for energy systems is given:

$$\begin{aligned} \min_{x} \quad & f(x) = (f_1(x), \dots, f_k(x))^{\mathrm{T}}, \\ \text{s.t.} \quad & x = (s, d, o), \quad s \in S,\ d \in D,\ o \in O. \end{aligned} \tag{1}$$

In this formulation, the vector f represents k usually conflicting objective functions f_k. The optimal solution of the multi-objective optimization is a set of solutions, such that improving one objective function worsens at least one other objective function. The solution set is so-called *Pareto set* or *Pareto front*, while each solution on the front is called *Pareto solution*[40]. A Pareto solution $\hat{x}$ must be *Pareto optimal*: There is no other feasible solution x satisfying the conditions $f(x) \le f(\hat{x})$ and, at the same time, $f_i(x) < f_i(\hat{x})$ for at least one objective function i. Depending on the scope of the synthesis and optimization problems of energy systems, a solution x in the objective function space may comprise of three independent decision-variable vectors s, d, and o, which belong to the continuous and/or integer variable spaces S, D, and O for the synthesis, design, and operation of the considered energy systems, respectively. On the synthesis level, the system structure is considered, i. e., the selection of units and interconnections among them; on the design level, sizing of the units employed is decided; and finally, on the operation level, the operational status (on/off) and loads are specified for each unit installed. The three synthesis levels correspond to an inherent hierarchical structure of energy systems [24]. To enable efficient superstructure-free optimization, the problem formulation (Eq. (1)) is decomposed into two levels: the upper level deals with the synthesis, while the lower level copes with the design and operation,

$$\begin{aligned} \min_{s} \ & f(s,d,o) = (f_1(s,d,o), \dots, f_k(s,d,o))^{\mathrm{T}}, \\ \text{s.t.} \quad & \min_{d,\,o} \quad f(s,d,o) = (f_1(s,d,o), \dots, f_k(s,d,o))^{\mathrm{T}}. \end{aligned} \tag{2}$$

The employed optimization algorithm exploits the bi-level formulation: the superstructure-free optimization employs a hybrid algorithm combining an evolutionary algorithm for the upper level with deterministic optimization for the lower level (Fig. 1). The upper-level evolutionary algorithm generates structural alternatives s, i. e., units selection and interconnections among the employed units, while each alternative generated by the upper level is then optimized deterministically in the lower level, i. e., identification of optimal sizing d and operation o of the employed units. The structural decisions s (Eq. (2)) are not explicitly modeled in a superstructure, but the structures are evolved with the new structural alternatives σ generated by an evolutionary algorithm. Consequently, the formulation of the multi-objective superstructure-free synthesis problem solved by the hybrid decomposition becomes

$$\begin{aligned} \min_{\sigma} & f(s(\sigma),d,o) = (f_1(s(\sigma),d,o), \dots, f_k(s(\sigma),d,o))^{\mathrm{T}} \quad \sigma \in \Sigma, \\ \text{s.t.} \quad & \min_{d,\,o} \quad f(s(\sigma),d,o) = (f_1(s(\sigma),d,o), \dots, f_k(s(\sigma),d,o))^{\mathrm{T}}, \end{aligned} \tag{3}$$

where the solution structure σ is evolved by mutation, and all structure alternatives in the space $\sum$ can be possibly reached by repeated structural mutation. In contrast to the spaces explicitly defined by superstructures, the space $\sum$ is not known in advance, and is only implicitly defined by the energy conversion hierarchy (ECH). The knowledge-integrated, generic ECH is a hierarchically-structured graph that classifies all considered energy conversion technologies according to their functions [39]. This classification enables an efficient definition of all reasonable connections between the considered energy conversion technologies. Thereby, a minimal set of generic replacement and insertion rules suffices to generate all feasible solution structures by structural mutations. More importantly, the manual definition of technology-specific replacement and insertion rules is avoided. For the upper-level evolutionary algorithm, a mutation operator has been designed in Ref. [39]. The mutation operator either randomly replaces units in a

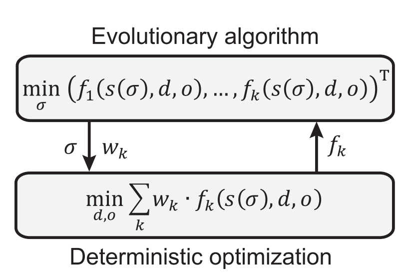

Fig. 1. Multi-objective superstructure-free optimization approach for multi-objective synthesis.