Energy 91 (2015) 700–711

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Superstructure-free synthesis and optimization of thermal power plants

Ligang Wang [a, b, c], Philip Voll [b], Matthias Lampe [b], Yongping Yang [a, *], André Bardow [b, **]

[a] School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beinong Road 2, Beijing 102206, China
[b] Chair of Technical Thermodynamics, RWTH Aachen University, Schinkelstraße 8, Aachen 52062, Germany
[c] Institute for Energy Engineering, Technical University of Berlin, Marchstraße 18, Berlin 10587, Germany

ARTICLE INFO

Article history:
Received 7 February 2015
Received in revised form
20 July 2015
Accepted 17 August 2015
Available online 20 September 2015

Keywords:
Thermal power plants
Evolutionary algorithms
Synthesis and optimization
Problem-specific mutation operator
Structural mutation
Structural optimization

ABSTRACT

The optimal synthesis and design of thermal power plants is best addressed using mathematical optimization techniques. However, conventional optimization methods require the user to manually define *a priori* the potential solution space through the modeling of a superstructure, which is a time-consuming, complex, and error-prone task. More importantly, the final superstructure model can not guarantee to contain all good alternatives (in particular, the optimal solution), while it might consider a huge number of meaningless or even infeasible alternatives. To circumvent the use of superstructures, recently, a generic superstructure-free optimization approach has been proposed by the authors to synthesize distributed energy supply systems. The approach employs hybrid optimization integrating evolutionary and deterministic optimization to enable simultaneous alternatives generation and optimization. In this paper, the approach is extended by a new mutation rule to enable the synthesis of thermal power plants. The features of the extended superstructure-free approach are illustrated by a case study. The optimization is initialized with the simplest plant cycle consisting of one turbine, one pump, one steam generator, and one condenser. The superstructure-free approach automatically identifies highly efficient and complex structures featuring multi-stage reheating and feedwater preheating.

1. Introduction

A key lever to address the well-known issues related to today's extensive use of fossil fuels [1–4] is the synthesis of highly efficient thermal power plants. However, the synthesis of thermal power plants is anything but a trivial task leading to complex design integrating many technologies [5–8]. Systematic methods have therefore been developed to guide the improvement of thermal energy systems, e.g., exergy-based analysis [9–12], entropy generation minimization method [13], and pinch technology [14]. These methods provide thermodynamic measures either to assess the quality of thermal power plants [9,14] or to formulate the objective functions in explicit relations with decision variables for parametric optimization [10]. These thermodynamic measures can be used in combination with economic measures [15,16] to improve the structure of the thermal power plant. However, these methods are not capable of generating structural alternatives automatically. It is well accepted that the optimal-synthesis task, i.e., the automatic generation and identification of configurations of a thermal power plant, is best addressed by mathematical programming, i.e., optimization methods [17–19].

For the optimization-based synthesis of energy systems, usually, superstructure-based optimization is employed [20–22]. In superstructure-based optimization, a superstructure model is analyzed by mathematical optimization algorithms to identify the best solution embedded in this model [23–25]. The superstructure-based approach has been extensively applied to the optimal synthesis of thermal power plants, e.g., combined-cycle co-generation plants [26,27], utility systems containing multiple extraction steam turbines [28,29], and coal-fired power plants [30,31]. However, the size of the employed mixed-integer nonlinear programming (MINLP) superstructure models tends to be very large for real-world problems, e.g. over 10^9 structural enumerations for the feed-water preheating train of thermal power plants [32]. Thus, computation time often becomes forbiddingly long for practical applications. However, even with greater computing power, the

* Corresponding author.
** Corresponding author.
E-mail addresses: yyp@necpu.edu.cn (Y. Yang), andre.bardow@ltt.rwth-aachen.de (A. Bardow).

http://dx.doi.org/10.1016/j.energy.2015.08.068
0360-5442/

fundamental problems of superstructure-based optimization would remain: On the one hand, good alternatives (in particular, the optimal solution) might be left out of the solution space spanned by the superstructure, while on the other hand a huge number of meaningless or even infeasible alternatives may be taken into account leading to forbiddingly large computational effort.

To overcome the fundamental problems of superstructure-based optimization, superstructure-free approaches have been proposed [33–35] to explore a practically unconstrained solution space using metaheuristic optimization [36], such as evolutionary algorithms [37]. In the superstructure-free approaches, the search space is not limited *a priori* by a superstructure model; instead, new solution structures are generated following randomized, heuristic search patterns, in search for the optimal solution.

In this fashion, Emmerich et al. proposed an evolutionary algorithm for superstructure-free optimization of chemical process systems [38] and the feedwater preheating systems of thermal power plants [33]. In their concept, the structure evolution is based on a large set of technology-specific mutation rules that have to be specified by the user manually. Manual specification of these mutation rules can be considered as difficult and error-prone as the manual definition of an appropriate superstructure model. Toffolo [35] has presented an advanced superstructure-free approach considering the thermodynamic features of thermal systems, thereby the approach is particularly tailored to the synthesis of thermal systems. In comparison to these approaches, a more *generic* concept that avoids any manual input for the definition of technology-specific mutation rules has been proposed by Voll et al. [34]. In the concept, technologies are placed into an energy conversion hierarchy (ECH), for which one set of generic mutation rules was designed once and for all. However, so far, this concept has only been applied to the synthesis of distributed energy supply systems.

In this paper, the superstructure-free approach proposed by Voll et al. [34] is generalized. In particular, the concept is extended for the synthesis of thermal power plants.

The paper is organized as follows. In Section 2, the original superstructure-free optimization framework as presented in Ref. [34] is briefly introduced. Next, this approach is extended for the optimization of thermal power plants (Section 3). An illustrative synthesis problem of a thermal power plant is discussed to evaluate the proposed approach (Section 4). Finally, the paper is summarized and conclusions are drawn (Section 5).

2. Superstructure-free optimization-based synthesis

Recently, a superstructure-free optimization approach has been proposed for the synthesis of distributed energy supply systems [34,39]. The superstructure-free approach employs a hybrid algorithm combining evolutionary with deterministic optimization. The upper-level evolutionary optimization generates structural alternatives, i.e., unit selection and interconnections, and the generated alternatives are optimized in the lower-level deterministic optimization, i.e., identification of optimal sizing and operation of the employed units. For the evolutionary algorithm, a mutation operator has been designed that randomly replaces units from a candidate structure by alternative designs. The manual definition of technology-specific replacement rules is avoided by using a knowledge-integrated, generalized approach based on the ECH. The ECH is a hierarchically-structured graph that classifies energy conversion technologies according to their functions. This classification enables an efficient definition of all reasonable connections between the considered conversion technologies. Thus, a minimal set of generic replacement rules suffices to generate all feasible solution structures by structural mutations.

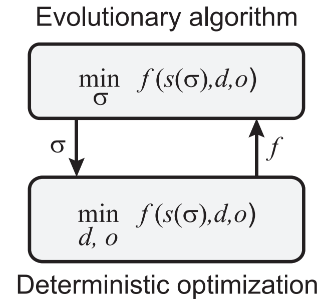

Fig. 1. Hybrid superstructure-free optimization approach (adapted from Ref. [39]).

The general mathematical programming problem for single-objective optimization of distributed energy supply systems is given by Ref. [39]:

$$\min_{s,\, d,\, o} f(s, d, o), \quad s \in S,\ d \in D,\ o \in O. \tag{1}$$

In this formulation, the decision variable vectors s, d, and o belong to the continuous and/or integer variable spaces S, D, and O that represent the synthesis, design, and operation decision variable spaces, respectively. On the synthesis level, the system structure is considered, i.e., which units are connected in which way; on the design level, the units' sizing is determined; and finally, on the operation level, the operational status (on/off) and operational loads are specified for each installed unit. The three levels correspond to an inherent hierarchical structure of energy systems [20]. Thus, the problem formulation can be decomposed into an upper level dealing with the synthesis, and a lower level dealing with design and operation:

$$\begin{aligned} &\min_{s} f(s, d, o), \\ &\text{s.t.} \quad \min_{d,\, o} \quad f(s, d, o). \end{aligned} \tag{2}$$

This bi-level formulation (Eq. (2)) is explored by the hybrid optimization method. In particular, the structural decisions s are not explicitly modeled in a superstructure, but an evolutionary algorithm continuously evolves new structural alternatives σ, which are then evaluated by deterministic optimization to determine optimal equipment sizing and operation (Fig. 1). The problem formulation of the hybrid optimization is given by

$$\begin{aligned} &\min_{\sigma} f(s(\sigma), d, o), \quad \sigma \in \Sigma, \\ &\text{s.t.} \quad \min_{d,\, o} \quad f(s(\sigma), d, o), \end{aligned} \tag{3}$$

where σ represents a solution structure evolved by mutation, and Σ represents the space of all structure alternatives possibly reached by mutation. In contrast to the space S (in Eq. (1)) explicitly defined in a superstructure, the space Σ is not known in advance and is only implicitly defined by the evolutionary algorithm.

2.1. Knowledge-integrated mutation operator for synthesizing distributed energy supply systems

The knowledge-integrated mutation operator employs replacement rules to generate new structures. The number of required replacement rules is minimized to a set of six meaningful replacement rules tailored to structural evolution of distributed energy supply systems: