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Robust optimal design of energy supply systems under uncertain energy demands based on a mixed-integer linear model

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ABSTRACT

In designing energy supply systems, designers should consider the robustness in performance criteria against the uncertainty in energy demands. In this paper, a robust optimal design method of energy supply systems under uncertain energy demands is proposed using a mixed-integer linear model so that it can consider discrete characteristics for selection and on/off status of operation and piecewise linear approximations for nonlinear performance characteristics of constituent equipment. First, a robust optimal design problem is formulated as a three-level min-max-min optimization one by expressing uncertain energy demands by intervals based on the interval programming, evaluating the robustness in a performance criterion based on the minimax regret criterion, and considering hierarchical relationships among design variables, uncertain energy demands, and operation variables. Then, a special solution method of the problem is proposed especially in consideration of the existence of integer operation variables. In a case study, the proposed method is applied to the robust optimal design of a cogeneration system with a simple configuration. Through the study, the validity and effectiveness of the method is ascertained, and some features of the obtained solutions are clarified.

1. Introduction

In energy supply systems, the values of performance criteria such as annual total cost, primary energy consumption, and CO_2 emission depend not only on design specifications but also on energy demands and corresponding operational strategies. Thus, it is important to determine design specifications optimally in consideration of operational strategies corresponding to seasonal and hourly variations in energy demands. However, many conditions under which energy demands are estimated have some uncertainty at the design stage, and thus the energy demands which occur at the operation stage may differ from those estimated at the design stage. Even if the optimal design is conducted in consideration of the estimated energy demands, the values of performance criteria expected at the design stage may not be attained at the operation stage. Therefore, designers should consider that energy demands have some uncertainty, evaluate the robustness in performance criteria against the uncertainty, and design the systems rationally in consideration of the robustness.

One of the rational approaches to the optimal design is to use mathematical programming methods, and they have been applied increasingly with the development of computation hardware and software. Especially, the mixed-integer linear programming (MILP) method has been utilized widely. This is because it can consider discrete characteristics for selection and on/off status of operation of equipment, and can also treat nonlinear performance characteristics of equipment by piecewise linear approximations. In addition, although the MILP method takes longer computation times than the linear programming method, it can obtain global optimal solutions more easily than the nonlinear programming method. In recent years, since commercial MILP solvers have become more efficient, they have been applied to the optimal design of small-scale commercial and residential energy supply systems in consideration of multi-period operation. However, most of the models used for the optimal design may not be sufficient. For example, Buoro et al., and Wakui and Yokoyama determined only the types of equipment with fixed capacities [1,2]. Lozano et al. and Carvalho et al. determined the types and numbers of equipment with fixed capacities [3–5]. Buoro et al. and Voll et al. determined the types and capacities of equipment, but treated the capacities as continuous variables [6–8]. Piacentino at al. and Zhou et al. used similar models, but did not take account of the dependence of

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performance characteristics of equipment on their capacities or part load levels [9,10]. On the other hand, Yokoyama and Ito, and Yang et al. proposed optimal design methods in consideration of discreteness of equipment capacities to resolve the aforementioned insufficiency of equipment models [11–13]. However, these studies were conducted under certain energy demands.

A simple way to evaluate the robustness in performance criteria under uncertain energy demands is to conduct a sensitivity analysis. Some studies are concerned with sensitivity analyses of performance criteria with respect to changes in energy demands. Ashouri et al. conducted a sensitivity analysis of the optimal design of a building energy system with respect to the changes in conditions related with energy demands and others, and they used deterministic and stochastic optimization approaches [14]. Wang et al. conducted a sensitivity analysis of the optimal design of a building energy system with respect to the changes in energy demands and others, and they used the genetic algorithm to solve the optimization problem [15]. Carvalho et al. conducted a sensitivity analysis to investigate the resilience of the optimal design of an energy system for a hospital with respect to the changes in energy demands and others, and they used an MILP approach for optimization [16]. To conduct such a sensitivity analysis, scenarios for the change in energy demands are inevitable. However, energy demands change with season and time, and there can be innumerable scenarios even if their intervals are given. Thus, it is necessary to limit the number of scenarios, and limited scenarios are not necessarily sufficient for the sensitivity analysis.

On the other hand, many papers on optimization of energy systems planning under uncertainty have been published. Verderame et al. reviewed many papers on planning and scheduling under uncertainty in multiple sectors, and reviewed some papers on energy planning [17]. Zeng et al. also reviewed many papers on optimization of energy systems planning under uncertainty [18]. In these review papers, the approaches adopted for optimization of energy systems planning were categorized into three ones: stochastic, fuzzy, and interval programming. However, it is difficult for designers to specify stochastic distribution and fuzzy membership functions for uncertain parameters in the first and second approaches. From the viewpoint of practical applications, it is much more meaningful for designers to specify fluctuation intervals for uncertain parameters in the third approach. Thus, this paper focuses on the third approach. Lin and Huang introduced an interval-parameter linear programming approach to energy systems planning [19]. Zhu et al. developed an interval-parameter full-infinite linear programming approach to energy systems planning under multiple uncertainties with crisp and functional intervals [20]. They also proposed an interval-parameter full-infinite mixed-integer programming approach to energy systems planning under uncertainties with functional intervals [21]. Dong et al. developed an interval-parameter minimax regret programming method for power management systems planning under uncertainty [22]. However, these methods do not consider the difference between design and operation variables whose values are determined at the design and operation stages, respectively. In addition, most of these methods cannot produce a unique optimal solution but an interval one, which cannot support the decision-making for design. Majewski et al. investigated the trade-off relationship in the objective function between the nominal and worst cases [23]. However, this method produces Pareto optimal solutions depending on the importance given to the nominal and worst cases, which is also unsuitable for design. Yokoyama and Ito proposed a robust optimal design method of energy supply systems in consideration of the economic robustness against the uncertainty in energy demands based on the minimax regret criterion [24]. This method is very natural because the design is determined so that the value of the objective function for the robust optimal design becomes as close as possible to that for the optimal design. In addition, this method considers that values of design and operation variables are determined at the design and operation stages, respectively, and produces a unique optimal solution. Yokoyama et al. revised this robust optimal design method so that it can be applied to energy supply systems with more complex configurations and larger numbers of periods set to consider variations in energy demands [25]. Assavapokee et al. presented a general framework for the robust optimal design based on the minimax regret criterion [26]. Although innumerable scenarios within intervals are considered in these methods, the used models for constituent equipment are not mixed-integer linear but only linear.

Therefore, it is strongly required to develop a robust optimal design method of energy supply systems based on a mixed-integer linear model, so that it can treat not only continuous but also discrete variables. At the first step for this challenge, the authors have proposed a method of comparing performances of two energy supply systems under uncertain energy demands based on a mixed-integer linear model for constituent equipment [27]. In this paper, a robust optimal design method of energy supply systems under uncertain energy demands is proposed using a mixed-integer linear model. A robust optimal design problem is formulated as a three-level min-max-min optimization one by expressing uncertain energy demands by intervals based on the interval programming, evaluating the robustness in a performance criterion based on the minimax regret criterion, and considering hierarchical relationships among design variables, uncertain energy demands, and operation variables. Although this formulation of the robust optimal design problem based on the mixed-integer linear model is similar to that based on the linear model, the solution method have to be changed substantially because of the existence of integer operation variables. In this paper, a special solution method is proposed especially in consideration of the existence of integer operation variables. In a case study, the proposed method is applied to the robust optimal design of a cogeneration system with a simple configuration, and the validity and effectiveness of the method is investigated.

2. Formulation of robust optimal design problem

2.1. Basic concept

In designing an energy supply system under uncertain energy demands, flexibility and robustness have to be taken into account [28]. The former means the feasibility in energy supply for all the possible values of uncertain energy demands, and is related with constraints. The latter means the sensitivity of performance criteria for all the possible values of uncertain energy demands, and is related with objective functions. In this paper, a robust optimal design method is proposed by which the robustness is improved while the flexibility is secured for all the possible values of uncertain energy demands. As a criterion for the robustness, the minimax regret criterion is adopted here [29]. Fig. 1 shows a basic concept of the robust optimal design based on the minimax regret criterion. The regret is defined as the difference in an objective function between non-optimal and optimal designs for some values of uncertain energy demands. The minimax regret criterion means that the values of design variables are determined to minimize the maximum regret for all the possible values of uncertain energy demands. Therefore, if this criterion is adopted, the difference in the objective function between the robust optimal and optimal designs can be small for all the possible values of uncertain energy demands.