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Development of a fuel management model for a multi-source district heating system under multi-uncertainty and multi-dimensional constraints

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ABSTRACT

In this paper, an interval single-sided fuzzy chance-constrained mixed-integer programming model is developed for the fossil fuel management of a multi-source district heating system under multiple uncertainties, where the heat-supply-capacity expansion planning can also be reflected. The non-dimensional comprehensive equations method is simultaneously improved to quantify the ambiguous heat provisions, utilized as a type of boundary condition inputs to the proposed model. A real-world case study of a heating system located in northeastern China is undertaken to show the feasibility and applicability of the proposed methods. To obtain the reasonable fossil-fuel management schemes, multi-dimensional constraints are incorporated into the model based on a comprehensive consideration in terms of fuel supply and demand, quality and quantity, economic cost and environment protection, as well as their interactions. Results obtained from the case study indicate that the solutions for both continuous and binary variables have been generated, which are useful for identifying suitable fuel-supply patterns and heat-source operational modes for a heating system under different system reliabilities and heating-load distribution states. In addition, the results also reveal that the fossil-fuel management and heating-capacity-expansion pattern, as well as the economic cost and pollutant emission performances are sensitive to the thermal coefficient and system reliability level, which may provide in-depth analyses of tradeoffs for further supporting robust fossil-fuel management under uncertainty.

1. Introduction

In northern China, heating system has played a significant role in providing residents with comfortable living environment during the space-heating period [1]. However, the excessive utilization of coals has brought a series of environmental problems such as the intensive emissions of atmospheric pollutants and GHG [2]. Moreover, some heating systems, especially those worn down by years, are still running with low efficiency, and may further aggravate pollution and result in high heating costs. To address the corresponding environmental and economic problems, the multi-source district heating system (MSDHS) has been gradually adopted during the last two decades, with the typical formation composed of the combined heat and power plant (CHP) to cover the basic space-heating demand and several peak-shaving heat sources (PHS) to compensate the peak heat load during the on-peak period [3]. However, with considering increasingly stringent pollutant-emission regulations and gradually-exhausted coal resources in China, merely improving the heating system structure (i.e. developing coal-fired MSDHSs) is not enough, and fuel management (FM) needs to be identically focused on from the point of view of better "source control" [4]. Therefore, the traditional FM needs to be greatly ameliorated, especially for the fossil-fuel-based MSDSHs in northern China.

In the recent decades, several research works have been conducted for FM from different perspectives [5–7]. For example, Yin et al. proposed a novel non-linear programming-based coal blending technology by utilizing neural network methods for fueling fixed bed, liquidized bed or other types of boilers in power plants [8]. Zhang and Hu presented a general biofuel supply chain model with mixed integer linear programming (MILP) technique to investigate the biofuel supply chain facility location as well as facility capacity at strategic levels, and

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biofuel production decisions at operational levels [9]. Guo et al. applied adaptive simulated annealing genetic algorithm into the coal blending optimization process with raw coal of different grades to satisfy the requirements of the end boilers [10]. Khoshahval et al. developed a new parallel optimization algorithm, P-PSOSA, in order to gain the possible minimum fitness value for the loading pattern optimization operation during suitable consuming runtime [11]. Poudel et al. developed a generalized Benders decomposition algorithm seeking to strengthen a bio-fuel supply chain system's multi-modal facility links while accounting for limited budget availability [12]. Li et al. proposed an inexact coal blending model based on the combination of interval programming and fuzzy linear programming, the model could help decision makers identify the optimal power coal blending schemes for the different boilers under four pollutants removal policy scenarios [13]. Fu et al. developed an interval two-stage double-stochastic programming model for FM of a district heating system fed with both fossil and renewable fuels under multiple random scenarios [14]. Summarily, most of these works tend to focus on deterministic modeling methods for supporting FM from one certain specific aspect (e.g. the fuel blending, the supply chain planning, or the fuel reloading operation). For a real-world MSDHS, the FM issue involves a complex decision-making process connected to many factors such as quality requirement, operation mode, cost control, thermo-economy, pollutant reduction, fuel availability and heat-demand, which make previous deterministic methods focusing on one certain specific aspect become infeasible [15]. Beyond that, most of those factors are closely linked and complicatedly interacted with each other, for instance, the economy-environment trade-off, and fuel-supply and heat-demand matching. However, previous research works do not effectively reflect and handle these system complexities existing in fossil FM within a general framework. Firstly, these researches mostly focused on either the fuel "quality" or the "quantity" issue to some extent, but few were found to address both issues concurrently for FM in a fossil-fuel-based MSDHS. It is of vital importance to couple fuel quality and quantity within a general model in that they would interact significantly in the FM framework [14]. For instance, the heating system may need less coal with high heating value or more coal with low heating value to ensure a satisfactory heating quality. Secondly, the previous researches seldom take the thermal coefficient of a MSDHS into consideration during the FM process [16]. This coefficient would play a significant role in FM because it could affect the fuel consumption mode through adjusting design heat provision assignment and the PHS-unit operation (e.g. the decision for uptime, heating-capacity expansion and switch-on/off temperature) [17]. However, it is constantly subjected to arbitrarily setting (i.e. either too high or low), bringing about a series of problems such as energy dissipation, high heating cost, pollutant and GHG emission increment, and unsatisfied space-heating quality [18]. A potential proper way may be to apply sensitive analysis technique to test the impact on the fuel-supply pattern, pollutant emission and heating cost performance within a certain range specified by Chinese regulatory authorities. Thirdly, there are a variety of uncertain factors lying in the MSDHS, such as residential heat demands, the fuel quality, the heating efficiency, as well as the associated economic implications [19,20]. Most of these uncertain factors would affect the FM process and need to be considered by decision makers because not only are these uncertainties connected with efficient fuel utilization, but also related to environmental protection and cost saving [21]. For example, most of the previous FM models corresponding to different fuel-combustion modes set the ideal coal-quality requirements at fixed values, based on which the boilers can be at an optimum function state. However, it is difficult to comply well with the ideal requirements due to coal price, coal type or some other technical reasons, and the coal-quality requirements are empirically evaluated and subject to decision maker or expert judgments, formulating the basic coal-quality requirements to enable the heating boiler to normally functioning but not at the optimum state [14]. This will lead to vague or ambiguous feature penetration into these requirements, nevertheless, there are seldom research works focusing on this issue. Besides, the volatile coal quality together with ambiguous coal-quality requirement may pose an unforeseen impact on combustion efficacy (i.e. heating effect), pollutant-emission intensity as well as heating cost, and the annual heat demand fluctuation due to the fickle climate change can further result in the heating cost and quality beyond control [22,23]. Thus, it is obvious that the uncertainties can significantly aggravate the FM complexities in MSDHSs, and such inherent uncertainties and complexities that exist in real-world MSDHSs have essentially placed them beyond the traditional deterministic optimization methods for FM [24]. If the above uncertainties in FM are ignored or simplified, the solutions of the applied optimization models may be unreliable or suboptimal, and even infeasible [25].

To quantify and deal with different system uncertainties and complexities, some researchers have developed various methods and employed them into the large-scale (e.g. urban or regional) energy management systems (EMS) [26,27]. Among them, the stochastic-based optimization methods, such as two-stage stochastic programming and chance-constrained programming, have been widely adopted, nevertheless, the mass-data requirements for formulating the probabilistic distribution potentially hinders their practical applications in the large-scale planning problems [28–30]. To overcome the data-driven uncertainty problems, the interval linear programming (ILP) developed by Huang et al. has attracted great attention in the past two decades due to its benign capability to deal with discrete intervals [31]. In addition to the advantage of less data requirement, its effective two-step interactive solution algorithm and the subsequent interval solutions with low uncertain degree contribute to the widespread acceptance and application of ILP in EMS [32–34]. These merits may provide an opportunity to handle multiple uncertainties lying in FM of a MSDHS. However, the ILP may become less effective when the right-hand side parameters are highly uncertain or expressed as fuzzy uncertainty, and it fails to allow for any violation of the system constraints under some reliability level (e.g. vague or ambiguous feature existing in coal-quality requirements) [35]. Fortunately, it is worth mentioning that the single-sided fuzzy chance-constrained programming (SFCCP), has been proposed as a potential way to tackle the "system reliability" problem, and has been successfully applied to practical EMS, although it may encounter difficulties in dealing with additional uncertainties that cannot be described by fuzzy sets [36]. Compared with those approaches for handling different uncertainties in large-scale EMS, there is still lack of effective methods for addressing the fossil FM problem for a MSDHS with multi-heating-source, multi-uncertainty-input, multi-expansion-option and multi-dimension-requirement features.

Generally, in response to the above challenges, an interval single-sided fuzzy chance-constrained mixed integer programming (ISFCCP-MI) method is proposed to address the FM problem in a fossil-fuel-based MSDHS, where an improved method is applied to quantify the ambiguous design heat provision. A real-world heating system case in northeastern China is utilized to demonstrate the applicability of the developed method with considering multiple constraints and multiple uncertainties. This research mainly contributes in the following aspects: (1) integrating ILP, SFCCP and mixed integer programming within a general framework to cope with multiple uncertainties and complexities lying in the FM process, (2) improving the traditional non-dimensional comprehensive equation method to quantify the ambiguous design heat provisions, (3) incorporating multi-dimensional constraints from various perspectives in the model to prompt the fossil FM schemes more practical in both fuel quality and quantity domain, and (4) generating fossil FM scheme, expansion planning and economy-environment performance under different system reliability levels and thermal coefficients to gain an in-depth insight to the fossil FM process. This paper will be organized as follows: Section 1 introduces research background, objective and significance. Section 2 proposes a computation method for quantifying the uncertain heat provisions, and illustrates the development process of ISFCCP-MI as well as its solution