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Robust optimization of hydrogen network

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ABSTRACT

Process integration is an effective way to reduce hydrogen utility consumption in refineries. A number of graphical and mathematical programming approaches have been proposed to synthesis the optimal network. However, as the operation of refineries encounters uncertainty with the rapidly changing market and deteriorating crude oil, existing approaches are inadequate to achieve robust hydrogen network distribution due to the uncertain factors. In this paper, robust optimization is introduced as a framework to optimize hydrogen network of refineries under uncertainty. In this framework, a number of scenarios representing possible future environments are considered. Both model robust and solution robust are explicitly incorporated into the objective function. A possible optimal network distribution which is less sensitive to the change of scenarios and has the minimum total annual cost is achieved by the tradeoff between the total annual cost and the expected error. Case studies indicate that this method is effective in dealing with hydrogen network design and planning under uncertainty in comparison to the deterministic approach and the stochastic programming method.

1. Introduction

Robustness is a topic that attracts a great deal of interest in industry especially for refineries and their subsystems. The rapidly changing market demands and deteriorating crude oil resources have exposed refineries to risk sensitive areas. Among various refinery subsystems, hydrogen network is more vulnerable to disturbances from the outside environment. It is well known that the hydrogen consumption of hydro-treating units is highly affected by sulfur content of the feed, while the hydrogen production from reformers varies because of restriction on the aromatic content and production planning. The fluctuation of these items may lead to solutions far from optimal or even cause infeasible situations. Therefore, refiners are seeking better operating patterns for their hydrogen networks to strengthen system robustness and maintain profitability.

During the past decade, plenty of work has been done in the design and operation of refinery hydrogen networks. The design methods fall into two categories [1]: pinch based conceptual methods and mathematical programming methods. Pinch based methods are intuitive and useful both in setting various targets like minimum hydrogen utility consumption [2–9], purifier capacity [10–14] and providing instructions for some practical constraints [15,16]. Mathematical methods [17–25] are capable of handling complicated problems such as multi-component [26], multi-purifier [27–29], multi-period [30,31] cases and even problems integrated with other subsystems [32,33]. However, the above methods are all adopting deterministic models, which do not take process uncertainties into consideration. Recently, Jiao et al. [34] employed a chance

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constrained programming method to evaluate the profit and process fluctuations. Xuan et al. [35] introduced the two-stage stochastic programming method that includes multiple scenarios of an uncertain future. These two approaches are effective in economic optimization under uncertain environments, but they did not consider the operation robustness whose importance has already been recognized in other fields. The development of robust optimization (RO) has been motivated by the limitations of these two approaches. Mulvey et al. [36] proposed the general formulation of robust optimization which optimized higher moments of the objective function and incorporated the expected error as violation of the control constraints. They also gave several advantages of the RO approach over sensitivity analysis and stochastic linear programming. Watkins et al. [37] introduced robust optimization into water resource planning to deal with risk and uncertainty of the possible future hydrological sequences. Yu and Li [38] simplified the objective functions proposed by Mulvey et al. [36] effectively. Based on this, Leung et al. [39] proposed a robust optimization model for multi-site production planning problem with uncertainty data. The results show that the RO model is more practical in dealing with uncertain economic scenarios. Sahinidis [40] presented a review on the approaches that deal with uncertainty optimization problems. Foo et al. [41] recently proposed robust linear programming model for the synthesis of empty fruit bunch allocation network under multiple biomass supply scenarios. The real life based case study shows that this approach can provide valuable decision support for the planning of the system. However, the robust optimization is mostly employed to deal with logistics problems. As we all know, hydrogen networks in refinery are also faced by many uncertain factors such as the content of sulfur in the crude oil and the price of hydrogen. Therefore, in this paper, we follow the method proposed by Mulvey to present a robust approach for the optimization of hydrogen networks. The rest of the article is organized as follows: in Section 2, a stochastic programming model for retrofit design problems will be modified to design problems. Section 3 will extend this model into the robust optimization version. Section 4 provides a case study to show the effectiveness of the proposed methods, while concluding remarks are given in Section 5.

2. Stochastic programming (SP) model for hydrogen networks

The hydrogen consumption of hydro-treating units is a typical example of model data that is usually known with some probabilistic distribution. Therefore, SP, in which uncertainty is indicated by the probability of scenario occurrences, can be introduced to this problem. Thus, the problem of hydrogen network design can be stated as: given a set of hydrogen demands, hydrogen producers as well as hydrogen utilities and a set of operating scenarios that include the operating pressure, stream flow rate and hydrogen concentration are also specified for the given units. The occurrence probabilities of the scenarios are also defined. The object is to optimize total annual cost of the network and the robustness of the network distribution confronted with the uncertainty of the environment is also taken into consideration.

The stochastic model involves two sets of variables: design variables and control variables. The design variables determine the structure of the process and the size of production units, while the control variables indicate the state of production in each scenario. The design variables are independent of any scenarios whereas the control variables depend both on design variables and uncertain parameters. For example, the pipeline connections, compressor existences, and so on constitute the design variables that are valid for all scenarios. Meanwhile, flow rate inside pipelines, operating capacity of purifiers are control variables.

The following notations are employed in the model formulation.

Sets
- I set of compressor
- J set of hydrogen source
- K set of hydrogen sink
- M set of purifier
- H set of utility
- S set of scenario

Parameters
- D distance of different units
- e price
- P pressure
- t the operation time

Variables
- Z total annual cost
- F flow rate of streams
- y hydrogen concentration of the stream
- Y binary variable denoting the existence of the connection
- C cost

Superscripts
- P the purified product
- R the tail gas of purifier

Subscripts
- s scenario
- i, i' compressor
- j hydrogen source
- k hydrogen sink
- h hydrogen utility
- m purifier
- fuel fuel
- power electricity consumption

2.1. Mass balance constraints

The mass balance constraints are constructed for every unit inside the network. All the possible stream connections are considered in these constraints, as shown in the following equations:

$$\sum_{m\in M} F_{h,m,s} + \sum_{i\in I} F_{h,i,s} + \sum_{k\in K} F_{h,k,s} = F_{h,s} \quad \forall h\in H,\ s\in S \tag{1}$$

$$\sum_{i\in I} F_{j,i,s} + \sum_{k\in K} F_{j,k,s} + \sum_{m\in M} F_{j,m,s} + F_{j,\text{fuel},s} = F_{j,s} \quad \forall j\in J,\ s\in S \tag{2}$$