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Research article

Equilibrium approach towards water resource management and pollution control in coal chemical industrial park

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A B S T R A C T

In this study, an integrated water and waste load allocation model is proposed to assist decision makers in better understanding the trade-offs between economic growth, resource utilization, and environmental protection of coal chemical industries which characteristically have high water consumption and pollution. In the decision framework, decision makers in a same park, each of whom have different goals and preferences, work together to seek a collective benefit. Similar to a Stackelberg-Nash game, the proposed approach illuminates the decision making interrelationships and involves in the conflict coordination between the park authority and the individual coal chemical company stockholders. In the proposed method, to response to climate change and other uncertainties, a risk assessment tool, Conditional Value-at-Risk (CVaR) and uncertainties through reflecting parameters and coefficients using probability and fuzzy set theory are integrated in the modeling process. Then a case study from Yuheng coal chemical park is presented to demonstrate the practicality and efficiency of the optimization model. To reasonable search the potential consequences of different responses to water and waste load allocation strategies, a number of scenario results considering environmental uncertainty and decision maker' attitudes are examined to explore the tradeoffs between economic development and environmental protection and decision makers' objectives. The results are helpful for decision/police makers to adjust current strategies adapting for current changes. Based on the scenario analyses and discussion, some propositions and operational policies are given and sensitive adaptation strategies are presented to support the efficient, balanced and sustainable development of coal chemical industrial parks.

1. Introduction

With the expansion of coal related industries, these water-intensive projects were constructed predominantly in arid western areas over the duration of the 12th Five-Year Plan (2011–2015) of China which will inevitably trigger a serious water crisis and exacerbate existing water scarcity problems (Li and Hu, 2017). Coal chemical industries are not only extremely water-intensive but also characterized by significant pollution with a large amounts of waste water directly into the river (Kavouridis and Koukouzas, 2008). The situation of severe water shortages, water pollution, and environmental degradation in coal chemical industrial areas has become increasingly serious and caused a major bottleneck in constraining sustainable economic and environmental development (Xie et al., 2010). Motivated by the conflicts between energy economy development and water resources and environmental protection, this paper aiming to improve the water utilization efficiency and minimize the industry's environmental impact and stresses the importance of regulated water resource allocation and pollution control strategy.

Nowadays, access to clean, affordable, reliable energy has been a cornerstone of the world's increasing prosperity and economic growth (Chu and Majumdar, 2012). With the development of clean coal technology, modern coal chemical industry has rapidly developed which is mainly involved with the production of clean energy and substitutes from diesel oil, gasoline, etc (China's National Energy Administration, 2015). It has been prioritized in

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recent years as it is expected to play a critical role in the sustainable development of energy resources (Xie et al., 2010; Man et al., 2017). The water resource scarcity and pollution problem have restricted the development of the coal chemical industry due to the reverse distribution of coal and water which is a prominent feature of China's resource endowments (Rubiocastro et al., 2010; Han et al., 2015). To battle with high water consumption and pollution that accompanies rapid industrial growth, most optimization studies have been focused on optimizing water exchange network or clean technology (Xiong et al., 2017). However, the associated problems of extensive energy use, water resource inefficiency, and heavy pollution have not been integrated to solve effectively (Tanaka et al., 2017; Shen et al., 2017).

With their increased resource efficiency and cleaner, more environmentally friendly production processes, coal-based energy parks have been seen as an efficient method to improve coal chemical industry sustainability (Lin and Long, 2015; Yune et al., 2016). Evidence has shown that encouraging a symbiotic relationship between the coal chemical plants in the same industrial park can significantly contribute to the sustainable development of the industrial activities (Boix et al., 2015). Industrial parks, which are established based on IE, have a number of independent companies and have the aim of concentrating economic development and the associated environmental pollution into a geographically confined area Ren et al. (2016). Therefore, these eco-industrial parks (EIPs) present both opportunities and challenges for environmentally sustainable industrial development Shi et al. (2010). While the industrial concentration in the parks makes it possible to achieve the proposed Sustainable Development Goals (SDG) Griggs et al. (2013); UN (2016) and gain economic and environmental benefits, this symbiosis between the industrial activities could lead to pollution and resource depletions that exceed local environmental carrying capacities. By applying a new paradigm of principles and system tools, IE provide concrete guidance for industrial park decision support activities Edgington (1995); Pauliuk et al. (2017). IE, as a solution-driven approach, integrates the environmental concerns into the production and resource utilization strategies with research having suggested a variety of practical initiatives. Comprised with those study which focused on certain point of resource or environmental problem, there has been less attention paid to developing a systematic, comprehensive methodology for reducing pollution, water resource saving, and increasing economic effectiveness (Zhang et al., 2015; Xinchun et al., 2017).

Water use and environmental protection problems have often been resolved using water allocation or quality control superstructure-based model, where the water is optimally distributed, treated and discharged in a region (Lovelady and El-Halwagi, 2009; Xie et al., 2017). Integrating water resource management and environmental protection through water and waste load allocations has also been studied for water resource and environment management in a river basin (Wang and Huang, 2011; Zeng et al., 2017a). Few total pollution control management techniques have been integrated into water environmental management systems of a industrial park. Therefore, to address this research gap, in this paper, total pollution, quality control, and water resource efficient allocations are integrated in a systematic model, in which the decision framework incorporates both the management objectives of the individual companies and the balanced development of the park as a whole, and accounts for the conflicting objectives of the participants who prioritize individual clean production based on IE and the park authority who prefers to focus on the overall economic growth while maintaining or improving the park's environmental performance (Leong et al., 2017).

The park authority and the coal chemical company stakeholders who the have conflicting objectives and preferences as decision makers are participated in the water resource and environmental management of the park. Decisions are made sequentially from the upper level to the lower level, with each level decision makers having different powers of control over the management objectives and decisions. Therefore, this decision situation fits with a decentralized decision system in which one leader and several followers of equal status are involved (Liu, 1998). A powerful tool dealing with this decision systems is the so-called bi-level programming (Wen and Hsu, 1991; Anandalingam and Apprey, 1991). And the conflict between economically efficient growth and environmental protection, or the tension between the economic utility of the natural resources and their ecological utility in the natural environment, has not been completely solved under EIP development as excessive water consumption and high emissions necessitate a trade-off between economic development and environmental sustainability. In this problem, to coordinate the relationship between the economy and the environment, a multi-objective method which involve more than one objective function is applied to model the optimal water and waste load allocations for the entire industrial park (Xu et al., 2011, 2016b; Leong et al., 2017). The set of solutions gained from multi-objective optimization model define the best tradeoff between competing objectives that is more in line with the problems being studied. As the external uncertainties in this integrated water resource and waste load allocation optimization model could result in different water and waste allocation strategies, a risk evaluator of the conditional value at risk (CVaR) which are employed to assess the impacts of degrees of the preference of decision makers on the tradeoff between system benefits and expected economic losses (Wang et al., 2017). And probability and fuzzy set theory are used to deal with uncertainty parameters and variables. Scenarios are then examined to evaluate the uncertainties related external environmental change, and the decision maker' attitudes, and to develop sensitive adaptation strategies to mitigate environmental damage and adapt to possible climate conditions (Wu et al., 2017). Motivated by the contradictions between economic development, environmental protection, and climate-change mitigation in the coal chemical industrial park, this paper develops an equilibrium approach for efficient energy conservation, water utilization and pollution control based on IE (Tang et al., 2015; Niu et al., 2017).

2. Key problem statement

To improve the efficiency of energy conservation, water utilization, and ensure environmental protection, a decision making framework, as shown in Fig. 1, is developed aiming at collective benefits achievement with equilibrium water and waste load allocation strategies.

2.1. Coordinating economic and environmental conflicts based on IE

Significant environmental problems rose with rapid development of coal chemical industrial, particularly as the worsening environmental conditions have resulted in major challenges to economic growth (Chu and Majumdar, 2012). By incorporating multi-objective procedures into the decision making process, the park decision maker attempts to balance the economic and environmental goals so that the proposed model is more realistic and results in an ecological solution to coal chemical industrial operations. As a multi-objective optimization problem is able to search