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Research article

Population-production-pollution nexus based air pollution management model for alleviating the atmospheric crisis in Beijing, China

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ABSTRACT

In recent years, increscent emissions in the city of Beijing due to expanded population, accelerated industrialization and inter-regional pollutant transportation have led to hazardous atmospheric pollution issues. Although a number of anthropogenic control measures have been put into use, frequent/severe haze events have still challenged regional governments. In this study, a hybrid population-production-pollution nexus model (PPP) is proposed for air pollution management and air quality planning (AMP) with the aim to coordinate human activities and environmental protection. A fuzzy-stochastic mixed quadratic programming method (FSQ) is developed and introduced into a PPP for tackling atmospheric pollution issues with uncertainties. Based on the contribution of an index of population-production-pollution, a hybrid PPP-based AMP model that considers employment structure, industrial layout pattern, production mode, pollutant purification efficiency and a pollution mitigation scheme have been applied in Beijing. Results of the adjustment of employment structure, pollution mitigation scheme, and green gross domestic product under various environmental regulation scenarios are obtained and analyzed. This study can facilitate the identification of optimized policies for alleviating population-production-emission conflict in the study region, as well as ameliorating the hazardous air pollution crisis at an urban level.

1. Introduction

In the past half century, the high speed of urbanization/industrialization has greatly improved human life globally, leading to population explosion, often with detrimental pressures on the environment (Tilman et al., 2002). Urban diseases such as air pollution and environmental crisis would emerge as the companions to excessive demographic expansion and industrial growth. These have become a global concern perceived to be the most significant issue facing the world today (Zeng et al., 2016). Particularly in some rapidly developed cities such as Beijing, China, the high speed of socio-economic changes corresponding to the inflow of external population without cautious regulation would aggravate disorder and drastic exploitation of industry and production, which have resulted in pollutant emissions exceeding the limits of environmental load. For example, in Beijing, from 2000 to 2015, the residential population increased from 13 to 20 million, which resulted in the GDP increasing 2.98 times; meanwhile, the pollutant emissions doubled and redoubled. Massive emissions associated with a high concentration of fine particulate matter (e.g., PM2.5) have led to a hazardous atmospheric pollution problem. Meanwhile, the latent danger from traditional pollutants (including SO2, NOx, and PM10) is perceived to be the most significant issue facing Beijing today (Kathleen et al., 2011).

Although a number of engineering control measures (such as treatment techniques and clean technologies) have been developed and applied to mitigate pollutant emissions, the scale of emissions in Beijing has exceeded the capacity of air diffusion and self-purification. Taking a panoramic view of the situation, an irrational industrial layout associated with rapid population expansion

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and high-speed production scale are the main causes of hazardous air pollution issues in the study region. Therefore, adjustment of the employed population structure and industrial layout pattern would be considered as important impacts on urban development strategies with a pollutant mitigation scheme in the future. In general, a rational urban development strategy can be rectified by a combination of a series of policies, such as population evacuation, adjustment of the employment structure, regulation of production scale, improvement of productive capacity, popularization of mitigation/clean technology, and transformation of environmental regulation/pollution control. Therefore, in the context of the frequent occurrence of hazardous air pollution, a population-production-pollution nexus (PPP) would be required to be built for providing a linkage between socio-economic development and environmental protection. This PPP system can be embedded into an air pollution management and air quality planning (AMP) initiative in Beijing, which can facilitate decision makers in adjusting current policies to obtain a complete and efficient plan for ensuring people's health and environmental sustainability (Zeng et al., 2016).

However, a variety of uncertainties incorporating natural and artificial conditions exist in a population-production-pollution nexus based air pollution management and air quality planning (PPP-AMP) system, which may intensify the conflict-laden issues of human activities and AMP (Li et al., 2006). For example, meteorological variations deemed as objective uncertainties exist in a PPP-AMP system with the random characteristics of natural processes such as diffusion process and climate change. Meanwhile, economic data (e.g., benefit and cost parameters) deemed as subjective uncertainties exist which would be impacted by some artificial errors of calculation and data deficiency. Moreover, industry-environmental policy is deemed as mixed uncertainty conditions. All the above uncertainties can influence the efficiency of a PPP-AMP plan. Even more important is that the interactions of the above uncertainties can lead to systemic complexities, which have challenged policymakers to generate desired decision alternatives (Huang, 1998; Tanaka et al., 2000; ApSimon et al., 2002; Li et al., 2006; Rapaport, 2010; Behera et al., 2014; Wang et al., 2013; Ichige et al., 2015).

Previously, various stochastic and fuzzy mathematical programming methods were developed for handling such challenges (Huang and Loucks, 2000; Nasiri et al., 2007; Li et al., 2013; Wang and Huang, 2013; Morais et al., 2014; Zeng et al., 2015). In general, fuzzy programming (FP) is adopted to describe the fuzziness of observed information, which can tackle vagueness in goals or constraints caused by natural imprecision (Liu and Liu, 2002; Zeng et al., 2014). For example, the input information such as losses for excess emissions is often difficult to obtain accurately; meanwhile, the diffusion and migration processes of pollution from various industrial plants are very unique and complex, which cannot usually be provided as a precise value for decision makers. Thus, a type of FP named fuzzy credibility constraint programming (FCP) can be introduced to handle the possibility and necessity of degrees of event occurrence, which is suitable for estimating the flexibility of results with a high degree of satisfaction (Inuiguchi, 2012). However, the method has difficulty in dealing with uncertainties expressed as probabilistic distributions. In a real case of PPP-AMP issue, meteorological variations such as wind velocity for diffusion and their frequencies of peaks are deemed as stochastic factors, the fluctuation of which can be associated with net system benefits; these uncertainties can be handled by stochastic programming (SP) presented as probabilistic distributions (Li et al., 2006; Zeng et al., 2015). However, for real-world problems, uncertainties expressed as nonlinear relationships can exist among many system components in which revenue and cost parameters were expressed as functions of pollutant emission and mitigation, which are a dilemma for TSP. Quadratic programming (QP) can reflect nonlinearity in cost/benefit objectives, and it has global optimum under a number of system conditions (Chen and Huang, 2001; Zeng et al., 2015). In fact, in practical PPP-AMP issues, multiple uncertainties are expressed in hybrid formats such as probabilities while existing as fuzzy membership functions, even nonlinearity in the left- and right-hand sides of constraints and in the objective function, which requires a mixed FCP and QP method within a two-stage context.

Therefore, the objective of this study is to develop a PPP-AMP for coordinating human activities and environmental protection. A fuzzy-stochastic mixed quadratic programming method (PPP-AMP-FSQ) can be proposed into PPP-AMP for handling uncertainties and systemic complexities, which cannot only handle uncertainties expressed as probability distributions but also quantify objective and subjective fuzziness in the processes of decision-making. Moreover, it can resolve nonlinear issues through quadratic functions. The proposed model is applied to a real case of AMP in Beijing, China. The results of the amount of adjusted industrial employment structure, reduced production scale, excess pollution emissions, reallocated industrial layout pattern, pollution mitigation scheme, and green gross domestic product (i.e., system benefit) under various environmental regulation scenarios are analyzed. It can also be used to identify an optimized industrial employment structure and industry-environmental policies for alleviating population-production-emission conflicts. It can also support a policymaker adjusting the current industrial structure pattern and pollution mitigation schemes in a robust manner associated with risk control.

2. Application

2.1. Overview of the study area

Beijing is situated on the northwest border of the North China Plain and covers an area of 16,807.8 km^2, containing 18 districts. The city is located in a warm temperate zone, and the prevailing wind throughout the year is northerly and northwesterly, becoming the strongest in spring (Dong et al., 2012). As a capital of China, it has undergone rapid urbanization/industrialization and economic growth in recent decades. By the end of 2013, the population of the basin exceeded 23.14 million; the rate of population growth reached 8.3% per year (BSY, 2013). The population growth and economic development accelerated the speed of urbanization processes; meanwhile human living standards and social material productivity have been promoted extremely. Until 2013, the GDP reached 1215.3 billion Yuan, which maintains a high growth rate of approximately 9% in recent years. The city has established a modern agricultural structure, developing peri-city modernistic agriculture, prioritizing cash crops, fruit tree plantation, and ecotourism. Meanwhile, Beijing has a fully integrated industrial structure that provides an important support to its economy. In 2013, GDP contributed by the secondary industrial sector achieved 485.55 billion Yuan (including 230.31 billion Yuan from industry and 55.24 billion Yuan from the construction industry), which promote the development of the social-economy of Beijing (BSY, 2013).

2.2. Problem statement

However, a number of urban environmental problems have been raised in response to the excessive population expansion and rapid industrialization, where air pollution is one of the most severe “urban diseases” that Beijing has to face. From 2000 to 2010,