Optimal PM2.5 emission reduction strategies for an industrial park based on China's 12th five-year plan on air pollution prevention and control

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Abstract

Over the past decades, China has been undertaking extremely rapid industrialization and urbanization. Along with economic boom, many adverse environmental effects are emerging. Among them, it is of great significance for the country to deal with air pollution such as PM2.5. As a compound pollutant, PM2.5 is composed of many significant pollutants (e.g., SO_2, NO_x, and TSP) that are closely related with many industrial activities in China. Till now, there have been few studies exploring and managing relationship between PM2.5 emission reduction and the associated industrial park that is a park to multiple industries such as power plants and manufacturing industries. This research introduced a supply-chain mechanism to systematically evaluate PM2.5 emission of industrial parks. To tackle the problems of PM2.5 emission reduction and industrial park management, an optimization model was proposed. Then the proposed model was applied into a pulp and paper industrial park to support the formulation of optimized strategies that can help fulfill the national plan. The results indicated that the reduction amounts of SO_2, NO_x, and TSP should be 126, 247, and 146 t per year in the manufacturing plant (i.e., a pulp mill in this research), and the reduction amounts of SO_2, NO_x, and TSP should be 291, 31, and 61 t per year in paper-making mill. Therefore, the proposed model was useful for management of air pollution as a decision tool in the level of a industrial park.

Keywords: optimization, PM2.5, pollution reduction, industrial park

Introduction

Air pollution is an issue of increasing public concern due to its recognized adverse effects on both environment and human health for decades (Lv et al. 2012). Generally, air-quality management problems are characterized by multiple pollutants. As air pollution arising from a variety of emission sources occurs in complex mixtures, people are always simultaneously exposed to diverse pollutants (Cohan et al. 2007). Recently, PM2.5 pollution has become an important aspect of Chinese urban air pollution. PM2.5 is an important pollutant in the atmosphere and proved to make greater contribution to visibility reduction (Ghim et al. 2005), incidence of respiratory diseases (Hong et al. 2002) and global climate change (Sloane et al. 1991) than larger size particle (Yang et al. 2013). The concentration of PM2.5 in China is much higher than that in America and Europe (Cheng et al. 2011) and PM2.5 has become the principal pollutant in most urban areas in China (Zhang et al. 2009; Yang et al. 2013). Studies have shown that, PM2.5 causes are complex. About 50% of PM2.5 come from coal, motor vehicles, dust, biomass burning, etc. Meanwhile, gaseous pollutants, such as sulfur dioxide, nitrogen oxides, and volatile organic compounds, can be changed into secondary fine particles through a complex chemical reaction (Zhu et al. 2012). Thus, it is very crucial to investigate the chemical characteristics and source apportionment of particulate matter, especially of fine particles during haze episodes(Zhang et al. 2013).

PM2.5 mainly originated from industrial activities, coal combustion, and traffic sources in many urban areas (Wang et al. 2013). In China, PM2.5 pollution and regional industrial activities are closely related. The region's industrial activity is often linked with the industrial parks. In China, after the policy of reform and opening up, the industrial park has gradually developed with the scale of economic activity. According to statistics released by the Ministry of Land, in 2011 the level of our country there are 208 national industrial parks, over 3000 regional industrial parks. With further increase of the level of industrialization, industrial parks played an important role in Chinese economy. Taking Beijing as an example, the output value of the city's industrial park in 2011 accounted for 24% of the region's total output value. Thus, the industrial park can be an important point for managing PM2.5 emission.

Previous studies on China PM2.5 emission were mainly composed by its spatial and temporal distribution, origin and chemical characteristics (Zhao et al. 2013; Feng et al. 2013). Because uncertainty character of PM2.5 emission data (Cooper et al. 1997; Huang and Loucks 2000; Lv et al. 2012), it is hard to analyze reduction of PM2.5 emission in industrial parks. In the study of environmental management of industrial parks, most researchers applied the theory of industrial ecology to determine material and energy exchange of the system to reduce the impacts of industrial activities. Since in industrial parks many enterprises are linked through the supply chains, a lot of scholars introduced life cycle analysis (LCA) to solve the distribution of matter and energy in the supply chains (Mattila et al. 2012; Davis et al. 2009). Also, there were some attempts in dealing with optimization on industrial and economic systems. Hugo and Pistikopoulos (2005) proposed a mathematical programming-based methodology including LCA criteria as part of the strategic investment decisions related to the design and planning of supply chain networks. Guillén-Gosálbez and Grossmann (2010) addresses the optimal design and planning of sustainable chemical supply chains (SCs) in the presence of uncertainty in the damage model used to evaluate their environmental performance. In the energy sector, Čuček et al. (2012) presents a MCO (multi-criteria optimization) of regional biomass supply chains for the conversion of biomass to energy through the simultaneous maximization of economic performance and minimization of the environmental and social footprints. However, none of these studies considers the LCI database itself as part of the superstructure to be used for supply chain synthesis (Gerber et al. 2013) and optimization.

Generally, air-quality management problems, such as PM2.5 reduction, are characterized by multiple pollutants (Lv et al. 2012). Thus, reduction of PM2.5 pollution in the industrial park should be added the consideration of contaminants category, business category, pollutant treatment and other factors. Previously, some optimization approaches were developed for air environment management. For example, Xu et al. (2013) develop an inexact fuzzy-random-chance-constrained air-quality management model. However, there are no studies to optimize the management study for PM2.5 pollution in industrial park scale. Generally, air-quality management problems are characterized by multiple pollutants. As air pollution arising from a variety of emission sources occurs in complex mixtures, people are always simultaneously exposed to diverse pollutants (Mayer 1999; Cohan et al. 2007; Lv et al. 2012). Therefore, the air-quality management strategies are not recommended to be constrained to address only individual criteria pollutants. Therefore, it is desired to develop a more advanced method to implement regional air-quality management in response to the above challenges.

Thus, the objective of this research is to propose an optimization model for supporting PM2.5 pollution reduction of an industrial park. In detail, this objective entails: (a) employment of supply-chain mechanism to systematically evaluate PM2.5 emission of industrial parks, (b) development of optimization model to tackle the problems of PM2.5 emission reduction and industrial park management, and (c) application of the proposed model in a pulp and paper industrial park to support the formulation of optimized strategies that can help fulfill the national 12th five-year plan on air pollution prevention and control (APPC).

Materials and Methods

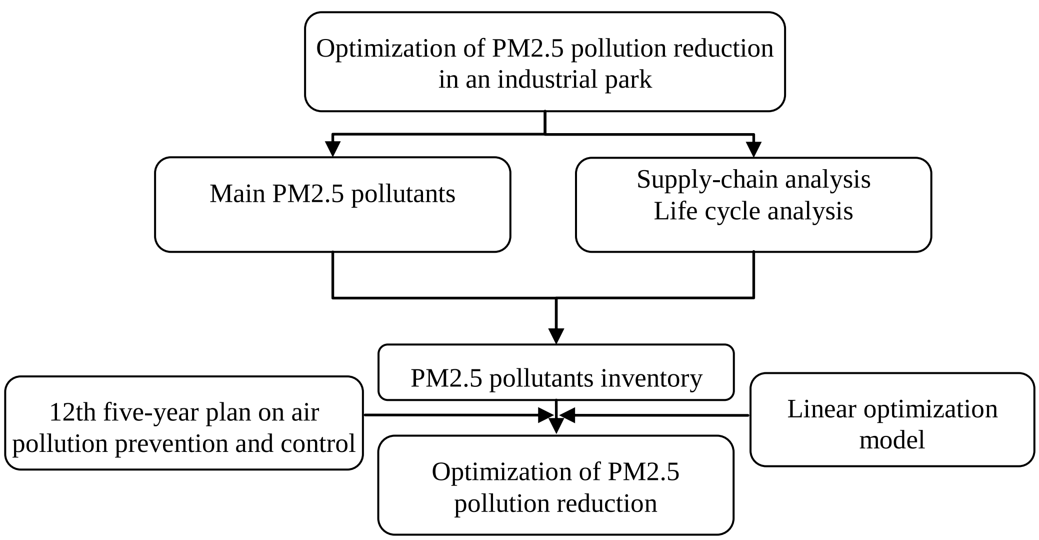

Fig. 1 Optimization system for PM2.5 emission reduction in an industrial park

Model formulation

Several related decisions must be made to control PM2.5 emission in the industrial park based on supply chains. An outline of the stock preparation problem is given in Fig. 1.

Assuming a manager of an industrial park is responsible for allocating government's PM2.5 reduction plan to factories. Because PM2.5 includes multiple pollutants and the industrial park includes multiple factories, the relevant stakeholders need to know how much reduction of PM2.5 emission need to be allocated to each factory, to fulfill minimum of investment and APPC. The optimization model in this article is focus on solving this allocation problem. First, according to a supply-chain analysis, a multi-objective programming concept model for industrial structure optimization is established as follows:

Objective: environmental investment

Subject to:

Constraint: the reduction plan of PM2.5 constraints

Maximizing economic benefit of the industrial park is chosen as the economic objective, and minimizing the discharge amount of PM2.5 emission, such as NOx, SO_2, VOCs, NH_3, TSP, is chosen as the environmental objective. Thus, the above concept model can be rewritten as follows:

Objective minimize environmental investment of PM2.5 emission

Subject to:

Constraint 1 the reduction plan of NOx constraints of APPC

Constraint 2 the reduction plan of SO_2 constraints of APPC

Constraint 3 the reduction plan of TSP constraints of APPC

Assuming the fixed treatment costs of PM 2.5 emission are d_1, d_2, and d_3, the annual treatment costs for per unit volume of PM 2.5 emission are e_1, e_2, and e_3, the amounts of PM2.5 emission are b_1, b_2, and b_3, the plans of PM2.5 emission in the t^{th} year are C_1, C_2 and C_3, and reduction amounts of PM2.5 emission are x_1, x_2, and x_3, the treatment cost f of PM2.5 emission can be described by Eq. (1).

$$f = m(d_1 + d_2 + d_3) + \sum_{q=1}^{m} e_1 x_{1q} + \sum_{q=1}^{m} e_2 x_{2q} + \sum_{q=1}^{m} e_3 x_{3q} \tag{1}$$

where q is factories of the industrial park, $q = 1, 2, \cdots, m$. The optimization model can be described by Eqs. (2).

Objectives:

$$\text{Min}\, f = m(d_1 + d_2 + d_3) + \sum_{q=1}^{m} e_1 x_{1q} + \sum_{q=1}^{m} e_2 x_{2q} + \sum_{q=1}^{m} e_3 x_{3q} \tag{2a}$$

Constraints:

$$\frac{x_{1q}}{b_{1q}} \geq C_1 \tag{2b}$$

$$\frac{x_{2q}}{b_{2q}} \geq C_2 \tag{2c}$$

$$\frac{x_{3q}}{b_{3q}} \geq C_3 \tag{2d}$$

$$d \geq 0 \tag{2e}$$

$$x \geq 0 \tag{2f}$$

$$e \geq 0 \tag{2g}$$

$$C \geq 0 \tag{2h}$$

Case study

Shandong Province is located in east longitude 114 °36 '~ 112 °43', latitude 34 °25'~ 38 °23' in eastern coastal China and with a land area of 157,100 km^2 and population of 95 million. There is one of the largest deltas in the province, namely the Yellow River Delta (Liu and Qi 2011). The delta is composed of large wetland areas (Liu and Qi 2011). Because oil and natural gas were discovered beneath Yellow River delta in the 1960s, the Yellow River Delta of Shandong Province has experienced rapid economic growth since economic reform started in the 1980s (Zhou et al. 1999; Shi and Qi 2012; Wang et al. 2011). Therefore, the province usually shares a big proportion of the nation or ranks among the top provinces (Han et al. 2010). A pulp and paper industrial park located in Shandong Province is chosen as a case in this paper. The main products of the industrial park are multiple types of copying paper. The main aim of this section is to optimize PM2.5 pollutants reduction from energy production to production of copying paper.

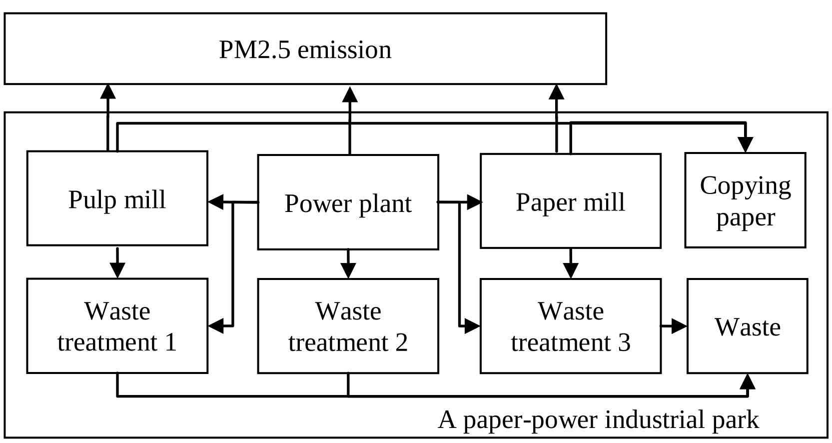

Fig.2 Framework of a paper-power industrial park

As showed in Fig. 2, there are a power plant, a pulp mill and a paper-making mill in an industrial park which discharge PM2.5 pollutants. These factories form paper-power industrial park. These factories are described into $A = \{A_1, A_2, A_3\}$. Suppose Factory A_1 is composed by m_1 processes, A_2 is m_2, and A_3 is m_3. The emission inventory of PM2.5 pollutants are showed in Eq. (3):

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1m_i} \\ b_{21} & b_{22} & \cdots & b_{2m_i} \\ \vdots & \vdots & \vdots & \vdots \\ b_{p1} & b_{p2} & \cdots & b_{pm_i} \end{pmatrix} \tag{3}$$

According to the study of life cycle analysis of copying paper from Yue et al. (2014). Using the model described in the section of methods, the inventory of PM2.5 pollutants 1000 kg of copying paper was described into Table 1.

Table 1 PM2.5 pollutants' inventories of producing 1000 kg copying paper in 2008

Industrial park	Pulp mill		Paper-making mill	
	Production period	Waste treatment	Production period	Waste treatment
Electricity -kWh	240	17.024	501	5.74

According to relevant research results from Chen S (Chen et al. 2012), the activity emission factors were listed in Table 2.

Table 2 Activity emission factor of power plants of China in 2007 -kg/kWh

PM2.5 pollutants	Amount
SO_2	5.03E-03
NO_x	5.45E-03
TSP	1.48E-03

The total production of copying paper is 810,000 t in this industrial park. Thus, the inventory of the industrial park is showed as follows:

Table 3 PM2.5 pollutants' inventories of producing 1t copying paper in 2008

Industrial park	Pulp mill			Paper-making mill		
	Production period	Waste treatment	Total	Production period	Waste treatment	Total
SO_2-kg	9.78E+05	6.94E+04	1.05E+06	2.04E+06	2.34E+04	2.06E+06
NO_x-kg	1.06E+06	7.52E+04	1.13E+06	2.21E+06	2.53E+04	2.24E+06
TSP-kg	2.88E+05	2.04E+04	3.08E+05	6.01E+05	6.88E+03	6.07E+05

According to the plan of PM2.5 pollutants reduction issued by Chinese government, up to the year of 2015 the amounts of SO_2, NO_x, TSP will be decreased by 12%, 13%, 10%. The goal of PM2.5 pollutants' reduction is set as 13% compared with the emission in the year of 2008. The average treatment cost of these PM2.5 pollutants are described by Table 4.

Table 4 PM2.5 pollutants' treatment cost

Type of treatment	Electrostatic dust collector	Facilities for selective catalytic reduction	Limestone gypsum method

Installation cost - E6 yuan		1.58	77.06	189
Operating cost - E6 yuan		3.98		37
Removal efficiency	NO_x - t/y	-	137	-
	SO_2 - t/y	-	-	30559
	TSP - t/y	142857	-	-

Result analysis and discussion

According to the plan of reduction, the industrial park should cut down the emission of SO_2, NO_x, TSP in the future of 5 years. Assuming the reduction amounts of SO_2, NO_x, and TSP in pulp mill are x_{11}, x_{12}, and x_{13} every year, and the reduction amounts of SO_2, NO_x, and TSP in paper mill are x_{21}, x_{22}, and x_{23} every year, Eqs. (2) are changed into the following equations.

$$\text{Min } f(t) = 189\times 2 + \frac{37\times 5(x_{11} + x_{21})}{30559} + \frac{77.06\times 5(x_{12} + x_{22})}{137} + 1.58\times 2 + \frac{3.98\times 5(x_{13} + x_{23})}{142857} \quad (4a)$$

Constraints:

$$\frac{x_{11}}{1050} \geq 0.12 \quad (4b)$$

$$\frac{x_{21}}{2060} \geq 0.12 \quad (4c)$$

$$\frac{x_{12}}{1130} \geq 0.13 \quad (4d)$$

$$\frac{x_{22}}{2240} \geq 0.13 \quad (4e)$$

$$\frac{x_{13}}{308} \geq 0.10 \quad (4f)$$

$$\frac{x_{23}}{607} \geq 0.10 \quad (4g)$$

The results shows that the minimized environmental investment of PM2.5 emission is 1615 million yuan. For pulp mill, the reduction amounts of SO_2, NO_x, and TSP are 126, 247, and 146 t per year. For paper-making mill, the reduction amounts of SO_2, NO_x, and TSP are 291, 31, and 61 t per year.

Conclusions

In this paper, supply-chain and life cycle methods and optimization model were proposed to systematically evaluate PM2.5 emission of industrial parks. The developed method could thus improve previous studies in systematically evaluating PM2.5 emission of industrial parks based on 12th five-year plan on air pollution prevention and control. Then the proposed methods and model were applied into a pulp and paper industrial park to support the formulation of optimized strategies that can help fulfill the plan. The results indicated that the reduction amounts of SO_2, NO_x, and TSP should be 126, 247, and 146 t per year in the manufacturing plant (i.e., a pulp mill in this research), and the reduction amounts of SO_2, NO_x, and TSP should be 291, 31, and 61 t per year in paper-making mill. However, due to a lack of the entire supply-chain and life-cycle data of the industrial park in Shandong Province, the PM2.5 emission in this industrial park was not analyzed in detail. The future study would be furthered in this area.

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