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ORIGINAL ARTICLE

A gaussian-box modeling approach for urban air quality management in a Northern Chinese City—II. pollutant emission abatement

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Abstract A modeling framework by linking air quality simulation with system optimization was presented in this paper to develop cost-effective urban air quality management strategies in Fengnan district of China. The relation between the total allowable emission and wind speed as well as the relation between the total allowable emission and air-quality-guideline satisfaction were quantified based on the simulation results of the Gaussian-box modeling system. The area-source emission reduction objective in each functional zone of the study city during the heating and non-heating seasons was calculated based on such relations. A linear programming model was then developed to optimize the emission abatement which was subject to a number of dust and SO_2 control measures. The economic objective of the air quality management strategy was to minimize the total emission control system cost while the environmental objective can still be satisfied. The environmental objective was reflected by the emission reduction objective of TSP, PM_{10} and SO_2 corresponding to an air-quality-guideline satisfaction percentage of 80%. Consequently, the modeling system comprehensively took into account the information of emission reduction objectives, emission abatement alternatives, emission reduction cost, and related resources constraints. An optimal emission abatement strategy and the related cost were obtained for various pollution control measures. The results would provide sound bases for decision makers in terms of effective urban air quality management and ensuring healthy economic development in the study city.

Keywords Air Pollution · Emission · Gaussian Plume Model · Multi-box Modeling · Optimization · Air Quality Management

1. Introduction

The urban air pollution problem in Fengnan district of northern China has received increasing attention in recent years since it not only directly affects the local economic development, but also poses a serious threat to the public health. Thus an effective air quality management (AQM) strategy is desired for this study city. A well-structured management system is usually related to a number of closely related components such as air quality monitoring, impact assessment, emission inventory, and emission abatement (Fedra and Haurie, 1999). Ideally, such a system should employ effective modeling tools for predicting air quality under complex source and meteorological conditions and for identifying cost-effective emission abatement strategies to keep

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the local air quality at a safe level (Parra-Guevara and Skiba, 2003).

Previously, many modeling studies were conducted to develop effective urban air pollutant emission control strategies through air quality simulation and optimization approaches. Such strategies may include imposing restriction on the total emission quantity of air pollutants or mandating specific emission reductions and control technologies (Ma *et al.*, 2001; Tourlou *et al.*, 2002). Specifically, the restriction of total emission quantity can be obtained by using the concept of atmospheric assimilative capacity which is the potential of atmosphere to absorb pollutants within certain limits without detrimental effects (Padmanabha and Tangirala, 1990). This capacity can be estimated through the air quality prediction models. For example, Manju *et al.* (2002) investigated the assimilative capacity of SO_2, NO_x and TSP in Manali of India for the four seasons by applying the industrial source complex short-term (ISCST-3) model; An *et al.* (2003) investigated the atmospheric environmental capacity of TSP during representative winter days in Lanzhou City of China by using the simulation results of the meso-scale atmospheric dispersion model HYPACT. Many other emission control studies were also reported by using the air quality simulation models. Mediavilla-Sahagun and ApSimon (2003) applied the air quality model USIAM to investigate the most cost-effective emission control strategy from a large number of road source emission reduction alternatives by exploring their resulting projected concentrations of PM_{10}; Qin and Oduyemi (2003) combined a receptor model and an atmospheric dispersion model to identify aerosol sources and estimate source contributions to air pollution in Dundee of UK; Peace *et al.* (2004) estimated the annual average NO_x emission and the related ambient air pollution contributions from road traffic sources by using the second generation ADMS-Urban Gaussian dispersion model. Some related studies can be found in Hao *et al.* (2001), Borrego *et al.* (2002), Krishna *et al.* (2004), and Fisher (2005).

In comparison to air quality simulation model, the mathematical optimization is another tool which can be used to identify cost-effective emission control strategies for meeting the desired air quality standards (Lou *et al.*, 1995; Liu *et al.*, 2003). Various studies were reported to address the air quality management problem by using an optimization approach such as linear programming, nonlinear programming, and integer programming. For example, Shih *et al.* (1998) developed a linear programming model for optimal control of photochemical pollutants by minimizing the net present value of emission control costs from various emission sources while meeting the ambient air quality goals over the planning time periods; Loughlin *et al.* (2000) developed a genetic algorithm-based optimization model for developing the urban-scale ozone control strategies by integrating a simple air quality model into the optimization process to represent ozone transport and chemistry; Ikeda *et al.* (2001) examined the optimal emission control strategy by developing the mixed-integer linear programming model based on the estimated sulfur emission for China in 2010; Wang and Milford (2001) developed a stochastic optimization model to investigate the optimal control strategies of urban ozone for achieving a specified air quality target with a given reliability, while the uncertainties in air quality simulation model were considered; Ma and Zhang (2002) developed a stochastic programming model to define the total allowable pollutant discharge of SO2 in Yuxi City of China; Dutta *et al.* (2003) developed a linear programming model to evaluate the impact of imposed maximum SO_2 emission limits on the operation and the profitability of a petroleum refinery in India in order to satisfy all relevant constraints due to the refinery configuration and operational limitations; Guariso *et al.* (2004) integrated a large photochemical model (CALGRID) with a multi-objective mathematical program to evaluate the emission abatement action priorities in Lombardy of Northern Italy. Other related studies can be found in Fedra and Haurie (1999), Yu *et al.* (2000), and Craig *et al.* (2001).

In general, the air quality prediction models and system optimization approaches have been used to deal with urban air quality management problems which involve a number of processes with socio-economic and environmental implications. However, the design of air quality management strategy is usually challenged by difficulties in simultaneously considering various information involving different-type emission sources, meteorological conditions, air quality objectives, emission abatement alternatives, cost of emission reduction, and related resources constraints (Crabbe *et al.*, 2000). Thus an effective modeling framework of linking air quality simulation with a system optimization model is required to address such difficulties. As part of the effort to determine effective urban air quality management strategy in Fengnan district of China, we developed a Gaussian-box modeling system which has the capability of effectively dealing with both point- and area-source emissions and reflecting the spatial variations in source distribution and meteorological conditions. The air quality simulation model development and verification has been described in an accompanying paper. The objective of this paper is then to develop an effective emission abatement strategy based on the developed simulation model. The contributions of various emission sources to the air quality (characterized by daily average concentrations of SO_2, TSP and PM_{10}) during the heating and non-heating seasons will be quantified using the simulation model. Based on such information, the pollutant emission reduction objectives can be determined in order to meet the air quality standards. A linear programming model will then be developed by minimizing the total emission control system cost. This optimization model will comprehensively consider the information of emission reduction objectives, emission abatement alternatives, emission reduction cost, and related resources constraints. Consequently an optimal emission abatement strategy will be obtained for improving air quality and ensuring healthy economic development in the study city.

2. Simulation of emission-source contribution to air quality

The daily concentrations of SO_2, TSP and PM_{10} are selected as important parameters for air quality management in this study. Based on the environmental quality objectives proposed by the local environmental agency of the study city, the 2nd level air quality criteria issued by CEPA (1996) is applied, namely 0.15, 0.30, and 0.15 mg/m^3 for SO_2, TSP, and PM_{10}, respectively. The environmental objective of the urban air quality management is that "the ambient pollutant concentration due to two types of emission sources (i.e. point- and area-source) will not exceed its corresponding air quality standard". Thus the contributions of both types of emission sources to the air quality in the study area need to be examined first.

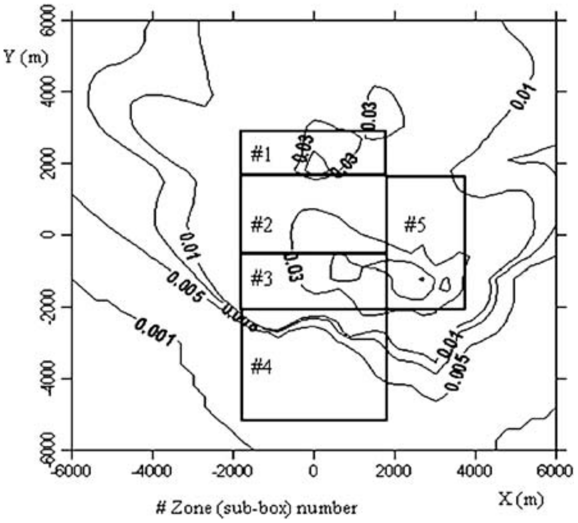

Fig. 1 Predicted SO_2 concentration contour due to point-source emission.

2.1. Point-source emission contribution

Based on the observed meteorological parameters during the heating and non-heating seasons, the point-source emission contribution to pollutant concentration in sub-boxes 1–5 in the modeling domain is simulated through the Gaussian dispersion model. This can be illustrated through computing the contribution to SO_2 concentration in each sub-box.Fig. 1 presents the predicted SO_2 concentration contour due to point-source emissions in the study city on December 17, 2002. The intersectional area between each contour and each sub-box is multiplied by the concentration value of that contour. The average point-source contribution to each sub-box is then calculated by dividing the summation of such multiplication values by the total area of that sub-box (i.e. weighted average).Table 1 lists the calculated point-source emission contributions to pollutant concentration in each sub-box on typical dates during the heating and non-heating seasons.

2.2. Area-source emission contribution

Table 2lists the observed meteorological data on typical dates during the heating and non-heating seasons. Based on such meteorological information, the 3-D multi-box model presented in the accompanying paper was then applied to predict the pollutant concentration

Table 1 Predicted point-source emission contribution to pollutant concentration in 2002 (unit: mg/m^3)

Date	Sub-box	TSP	SO_2	PM_{10}	Date	Sub-box	TSP	SO_2	PM_{10}
09.24	1	0.010	0.010	0.010	12.11	1	0.010	0.025	0.002
	2	0.008	0.008	0.004		2	0.008	0.010	0.003
	3	0.006	0.008	0.006		3	0.010	0.010	0.002
	4	0.005	0.007	0.005		4	0.010	0.010	0.002
	5	0.020	0.040	0.015		5	0.020	0.030	0.010
09.25	1	0.010	0.010	0.010	12.12	1	0.010	0.005	0.003
	2	0.007	0.008	0.004		2	0.008	0.010	0.005
	3	0.010	0.008	0.006		3	0.008	0.010	0.005
	4	0.006	0.007	0.004		4	0.006	0.010	0.003
	5	0.020	0.030	0.015		5	0.020	0.030	0.010
09.26	1	0.015	0.015	0.010	12.13	1	0.015	0.015	0.005
	2	0.010	0.008	0.005		2	0.010	0.008	0.008
	3	0.010	0.010	0.006		3	0.015	0.010	0.005
	4	0.007	0.008	0.007		4	0.007	0.008	0.002
	5	0.025	0.020	0.015		5	0.010	0.015	0.003
09.27	1	0.020	0.030	0.002	12.14	1	0.030	0.030	0.008
	2	0.020	0.008	0.003		2	0.015	0.020	0.010
	3	0.015	0.010	0.002		3	0.015	0.020	0.008
	4	0.008	0.005	0.002		4	0.010	0.015	0.003
	5	0.010	0.010	0.005		5	0.015	0.010	0.010
09.28	1	0.010	0.030	0.002	12.17	1	0.015	0.020	0.005
	2	0.008	0.010	0.005		2	0.010	0.010	0.008
	3	0.005	0.007	0.002		3	0.010	0.020	0.005
	4	0.008	0.002	0.003		4	0.010	0.010	0.002
	5	0.030	0.030	0.025		5	0.010	0.020	0.003
09.29	1	0.010	0.025	0.003	12.18	1	0.015	0.020	0.005
	2	0.008	0.008	0.004		2	0.010	0.010	0.003
	3	0.007	0.005	0.004		3	0.010	0.020	0.003
	4	0.006	0.008	0.004		4	0.008	0.010	0.003
	5	0.030	0.030	0.020		5	0.010	0.015	0.006

in each sub-box due to the area-source emissions. Table 3presents the calculated area-source emission contribution to the daily average concentrations of TSP, SO_2, and PM_{10} on typical dates, respectively. It is observed that the TSP and PM_{10} concentrations due to area-source emissions exceed their corresponding air quality standards during the heating season, with TSP concentration ranging from 0.3554 to 0.4736 mg/m^3 and PM_{10} ranging from 0.1648 to 0.2427 mg/m^3, respectively. Only a few of the calculated SO_2 concentrations in sub-box 2 due to area sources exceeds its corresponding air quality criteria, with concentration ranging from 0.0939 to 0.1649 mg/m^3. These prediction results well match the monitoring results. During the non-heating season, the TSP and PM_{10} concentrations are also above their corresponding air quality standards, with TSP ranging from 0.3135 to 0.3818 mg/m^3 and PM_{10} ranging from 0.1592 to 0.2229 mg/m^3, respectively. All of the predicted SO_2 concentrations are below the air quality guideline, ranging from 0.0228 to 0.0388 mg/m^3.

3. Determination of emission reduction objectives

3.1. Allowable area-source emission contribution

It is found from Tables 1 and 3 that the contribution of point-source emissions to the pollutant concentration in each sub-box is very small as compared to that of area-source emissions. Under the current situations of industrial activities in the study city, the number of point sources (with stack height above 35 m) is relatively small. Most of these point sources are industries associated with relatively big companies which already have high-efficiency pollution control facilities, and there are only very small rooms for them to

Table 2 Meteorological data observed on typical dates in the heating and non-heating seasons

Date	Wind-direction group	Average wind speed (m/s) At height <200 m	Average wind speed (m/s) At height >200 m	Date	Wind-direction group	Average wind speed (m/s) At height <200 m	Average wind speed (m/s) At height >200 m
09.24	E	2.5	4.91	12.11	E	1.4	2.9
	S	2.3	4.52		S	1.3	2.74
	W	2.4	4.71		W	1.6	3.37
	N	3.5	6.68		N	1.05	2.21
09.26	E	2.2	4.32	12.12	E	1.9	4.01
	S	2.0	3.93		S	1.4	2.95
	W	2.5	4.91		W	2.0	4.22
	N	2.6	5.11		N	1.1	2.32
09.27	E	1.2	2.36	12.13	E	2.9	6.12
	S	1.3	2.55		S	2.7	5.69
	W	1.1	2.16		W	3.2	6.75
	N	1.5	2.95		N	2.5	5.27
09.28	E	2.3	4.52	12.14	E	1.1	2.32
	S	2.2	4.32		S	1.0	2.11
	W	3.0	5.90		W	1.2	2.53
	N	2.7	5.31		N	1	2.11
09.29	E	2.8	5.51	12.18	E	2.4	5.06
	S	2.5	4.91		S	2.4	5.06
	W	2.6	5.11		W	2.8	5.9
	N	2.3	4.52		N	1.7	3.58

further reduce the pollutant emissions. As a result, an effective way is to reduce the area-source emissions in order to meet the air quality standards in the study city. By assuming the point-source emission contribution to each sub-box as a constant (as listed in Table 1), the allowable pollutant concentration contribution due to area sources is then calculated as follows:

$$C_{iAj} = C_{iS} - C_{iPj} \qquad (1)$$

where C_{iAj} is allowable concentration contribution for pollutant i in sub-box j ($j = 1, 2, \ldots, 5$) due to area sources, C_{iS} is air quality standard for pollutant i, C_{iPj} is point-source contribution to the concentration of pollutant i in sub-box j ($j = 1, 2, \ldots, 5$). The allowable area-source contribution to the pollutant concentration in heating and non-heating seasons are then calculated and listed inTable 4.

3.2. Relation between total allowable emission and wind speed

A trial-and-error method was used to implement the 3-D multi-box model by proportionally reducing the area-source emission rates in the study area to predict the pollutant concentration in each sub-box. If the predicted concentration is greater than the corresponding allowable pollutant concentration as listed in Table 4, the area-source emission rates were further reduced to run the model until all the prediction results were less than the corresponding allowable values. As a result, the allowable area-source emission rate corresponding to the allowable area-source emission contribution in each sub-box can then be obtained. The total allowable emission rate from both point and area sources will then be calculated by summing the allowable area-source emission rate and the point-source emission rate in the study city. According to Table 6 in the accompanying paper, the investigated total point-source emission rate in the study area is 36189.33, 40467.33, and 24608.73 kg/d for TSP, SO_2, and PM_{10}, respectively. Thus by using this trial and error approach, the relationship between the total allowable emission rate and average wind speed was established.Figs. 2,3 and 4 present the regression curves between total allowable pollutant emission rate and average wind speed during the heating and non-heating seasons, respectively. It is observed from these figures that the allowable pollutant

Table 3 Predicted area-source emission contribution to pollutant concentration in 2002 (unit: mg/m^3)

Date	Sub-box	TSP	SO_2	PM_{10}	Date	Sub-box	TSP	SO_2	PM_{10}
09.24	1	0.3158	0.0279	0.1615	12.11	1	0.4010	0.1035	0.1930
	2	0.3324	0.0316	0.1741		2	0.4731	0.1554	0.2424
	3	0.3175	0.0228	0.1655		3	0.4214	0.0944	0.2116
	4	0.3205	0.0288	0.1647		4	0.4367	0.1014	0.2239
	5	0.3183	0.0283	0.1619		5	0.4324	0.1053	0.2155
09.25	1	0.3152	0.0279	0.1610	12.12	1	0.4011	0.1029	0.1850
	2	0.3317	0.0315	0.1736		2	0.4734	0.1485	0.2287
	3	0.3168	0.0228	0.1650		3	0.4214	0.0948	0.2025
	4	0.3195	0.0287	0.1638		4	0.4368	0.1011	0.2144
	5	0.3170	0.0281	0.1606		5	0.4325	0.1041	0.2055
09.26	1	0.3206	0.0285	0.1660	12.13	1	0.3554	0.1030	0.1648
	2	0.3394	0.0326	0.1805		2	0.4011	0.1329	0.1928
	3	0.3239	0.0232	0.1716		3	0.3689	0.0965	0.1751
	4	0.3271	0.0296	0.1711		4	0.3812	0.1007	0.1826
	5	0.3232	0.0289	0.1661		5	0.3769	0.1039	0.1781
09.27	1	0.3543	0.0324	0.2000	12.14	1	0.4012	0.1053	0.1931
	2	0.3818	0.0388	0.2229		2	0.4736	0.1649	0.2427
	3	0.3592	0.0240	0.2089		3	0.4215	0.0939	0.2117
	4	0.3635	0.0342	0.2085		4	0.4368	0.1017	0.2239
	5	0.3606	0.0335	0.2031		5	0.4326	0.1072	0.2156
09.28	1	0.3159	0.0280	0.1616	12.17	1	0.3661	0.1024	0.1730
	2	0.3340	0.0318	0.1756		2	0.4203	0.1393	0.2089
	3	0.3195	0.0231	0.1675		3	0.3811	0.0957	0.1880
	4	0.3227	0.0291	0.1670		4	0.3949	0.1007	0.1979
	5	0.3180	0.0283	0.1613		5	0.3902	0.1037	0.1905
09.29	1	0.3135	0.0276	0.1592	12.18	1	0.3644	0.1023	0.1666
	2	0.3318	0.0316	0.1733		2	0.4181	0.1375	0.1990
	3	0.3188	0.0232	0.1665		3	0.3823	0.0960	0.1793
	4	0.3234	0.0291	0.1679		4	0.3961	0.1008	0.1883
	5	0.3189	0.0284	0.1624		5	0.3898	0.1036	0.1822

emissions will increase with the wind speed, due to the increase of pollutant dispersion.

3.3. Relation between total allowable emission and air-quality-guideline satisfaction

In order to develop an effective air quality management strategy suitable for the local situation of the study city, here we introduce the concept of air-quality-guideline satisfaction percentage which is defined as follows:

$$\eta = \frac{N_s}{N} \times 100\% \qquad (2)$$

where η is the air-quality-guideline satisfaction percentage (%), N$_s$ is the number of days when the pollutant concentrations are below the corresponding air quality standards during the heating or non-heating season, and *N* is the total number of days of a heating or non-heating season. In this study, *N* is selected as 120 for the heating season and 245 for the non-heating season, respectively.

The average wind speed is estimated for a certain value of the air-quality-guideline satisfaction percentage. For example, a percentage value η of 80% for the heating season corresponds to N_s of 96 days, and the mean wind speed for these 96 days during the 120-day heating season is then estimated by statistically analyzing the observed wind-speed data from 2000 to 2002. The corresponding total allowable pollutant emission rate was obtained from Figs. 2–4 by knowing this average wind speed value. Accordingly, the predicted total allowable pollutant emission rates under different air-quality-guideline satisfaction percentage scenarios were plotted in Figs. 5–7, respectively. For example, when η is 80%, the total allowable emission

Table 4 Allowable area-source emission contribution to pollutant concentration in 2002 (unit: mg/m^3)

Date	Sub-box	TSP	SO_2	PM_{10}	Date	Sub-box	TSP	SO_2	PM_{10}
09.24	1	0.290	0.140	0.148	12.11	1	0.280	0.125	0.140
	2	0.292	0.142	0.147		2	0.285	0.140	0.146
	3	0.294	0.142	0.148		3	0.285	0.140	0.144
	4	0.294	0.143	0.148		4	0.290	0.140	0.145
	5	0.280	0.110	0.140		5	0.280	0.120	0.135
09.25	1	0.290	0.140	0.147	12.12	1	0.280	0.125	0.140
	2	0.293	0.142	0.145		2	0.290	0.140	0.146
	3	0.295	0.142	0.145		3	0.285	0.140	0.144
	4	0.294	0.143	0.147		4	0.290	0.140	0.146
	5	0.280	0.120	0.140		5	0.280	0.120	0.135
09.26	1	0.285	0.135	0.145	12.13	1	0.285	0.125	0.140
	2	0.290	0.142	0.142		2	0.290	0.142	0.145
	3	0.290	0.140	0.145		3	0.290	0.140	0.144
	4	0.293	0.142	0.148		4	0.293	0.142	0.143
	5	0.275	0.130	0.147		5	0.290	0.125	0.135
09.27	1	0.280	0.120	0.142	12.14	1	0.270	0.120	0.148
	2	0.280	0.142	0.140		2	0.285	0.130	0.147
	3	0.285	0.140	0.142		3	0.285	0.130	0.148
	4	0.292	0.145	0.147		4	0.285	0.135	0.148
	5	0.290	0.140	0.140		5	0.270	0.140	0.145
09.28	1	0.290	0.120	0.145	12.17	1	0.285	0.130	0.148
	2	0.292	0.140	0.142		2	0.290	0.140	0.145
	3	0.295	0.143	0.145		3	0.290	0.130	0.148
	4	0.292	0.148	0.148		4	0.290	0.140	0.147
	5	0.270	0.120	0.147		5	0.290	0.130	0.125
09.29	1	0.290	0.125	0.145	12.18	1	0.285	0.130	0.147
	2	0.292	0.142	0.147		2	0.290	0.140	0.146
	3	0.293	0.145	0.147		3	0.290	0.130	0.146
	4	0.294	0.142	0.147		4	0.292	0.140	0.146
	5	0.270	0.120	0.144		5	0.290	0.135	0.130

rates from both point and area sources are 59622.10 and 68372.61 kg/d for TSP, 51704.50 and 71578.79 kg/d for SO_2, 31803.68 and 35830.34 kg/d for PM_{10} during the heating and non-heating seasons, respectively. It is illustrated from these figures that the allowable pollutant emission rate for the non-heating season is greater than that for the heating season under the same air-quality-guideline satisfaction percentage. Under a

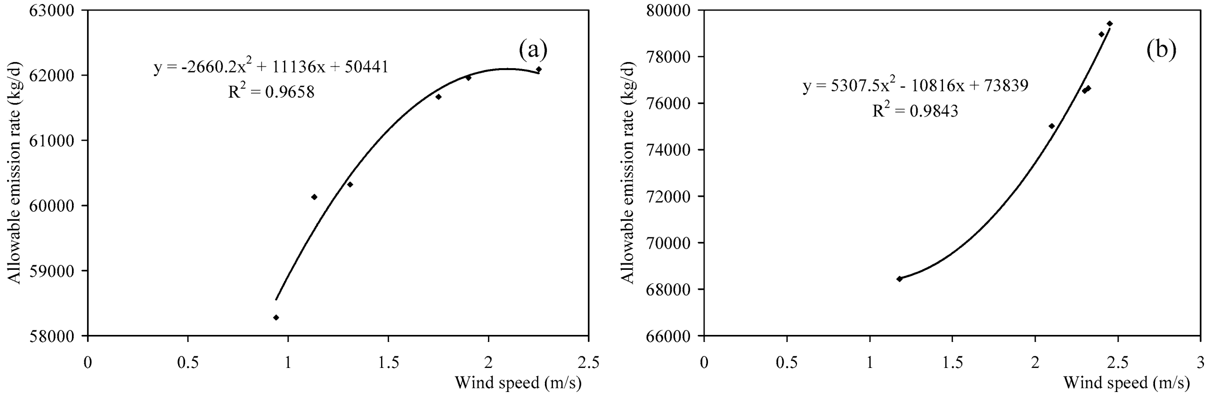

Fig. 2 Regression curve between total allowable TSP emission rate and average wind speed, (a) heating season, (b) non-heating season.

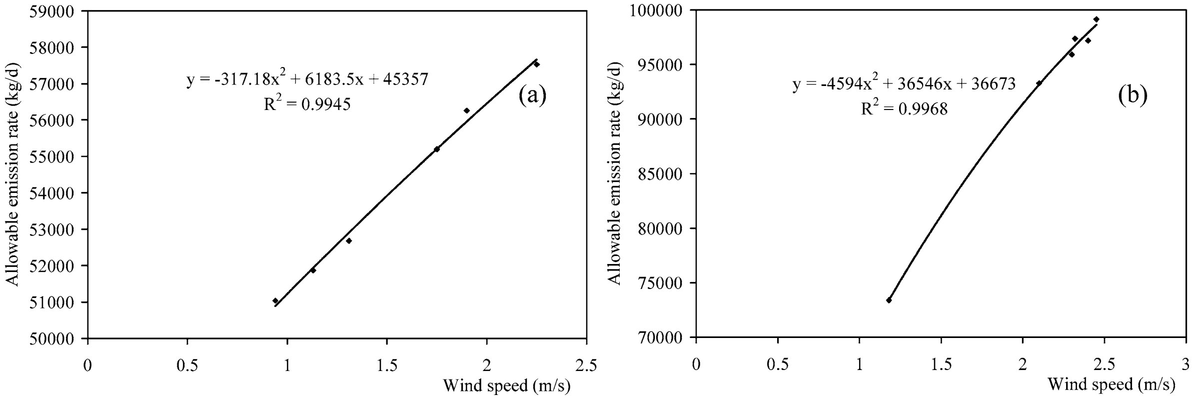

Fig. 3 Regression curve between total allowable SO_2 emission rate and average wind speed, (a) heating season, (b) non-heating season.

certain required η value, the total allowable pollutant emission per year can then be calculated based on the regression models presented inFigs. 5–7.

3.4. Emission reduction objectives

As indicated in section 3.1, the emission abatement strategy in the study city should focus on the area-source emissions. After the determination of the total allowable emission rate under different air-quality-guideline satisfaction percentages, the area-source emission reduction objective in each sub-box can be calculated. This is facilitated by firstly computing the allowable area-source emission (AASE) rate from each sub-box on typical dates using the 3-D multi-box model (as discussed in section 3.2). Then the ratio (ϕ) of the average AASE rate of each sub-box to the total AASE of the five sub-boxes can be calculated. The AASE rate from each sub-box under a certain air-quality-guideline satisfaction percentage η can be obtained by multiplying the total AASE rate of the study city under η by the ratio ϕ. The emission reduction objective for each sub-box is then calculated by subtracting the current area-source emission rate in that sub-box from the corresponding AASE rate. The related calculation results for the heating and non-heating seasons are listed in Tables 5 and 6,respectively. For example, the average calculated AASE rate of SO_2 during the typical dates of heating season is 1006.77, 3204.33, 1822.18, 4113.67 and 2224.59 kg/d for sub-box 1–5, corresponding to the ratio (ϕ) of 8.14%, 25.90%, 14.73%, 33.25% and 17.98%, respectively (see Table 6). As described in section 3.3, the total allowable emission rate of SO_2 from both point and area sources is 51704.50 kg/d during the heating season. The investigated total point-source emission rate of SO_2 is 40647.33 kg/d (see section 3.2). The additional point-source emission rate of SO_2 from heating boilers in the heating season is 1076.3 kg/d as listed in Table 7of the accompanying paper. Thus, the total allowable area-source emission rate for the study

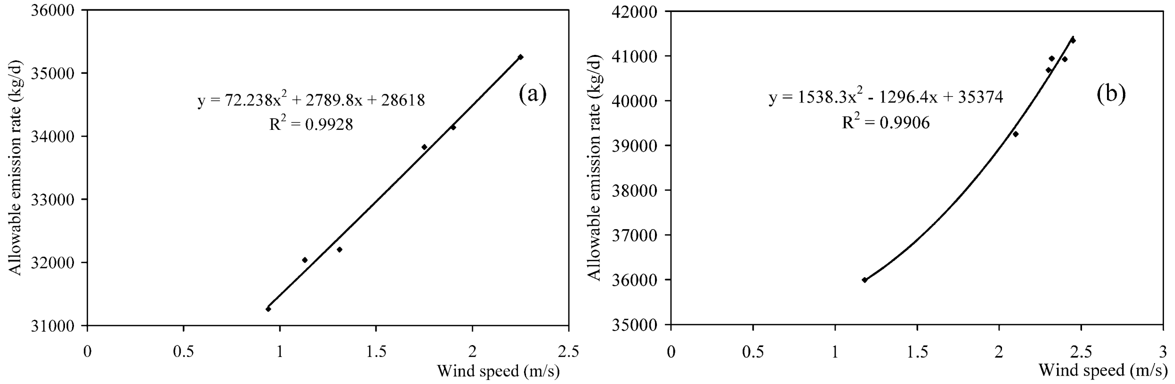

Fig. 4 Regression curve between total allowable PM_{10} emission rate and average wind speed, (a) heating season, (b) non-heating season.

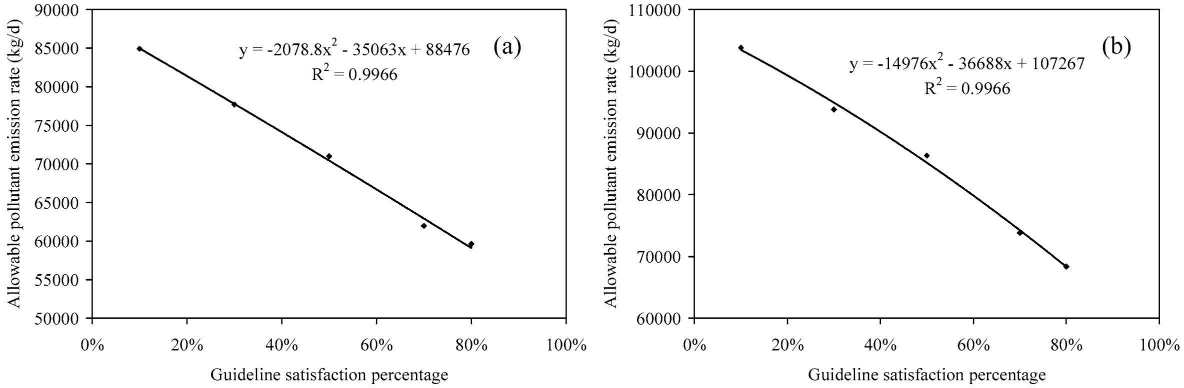

Fig. 5 Regression curve between total allowable TSP emission rate and air-quality-guideline satisfaction percentage, (a) heating season, (b) non-heating season.

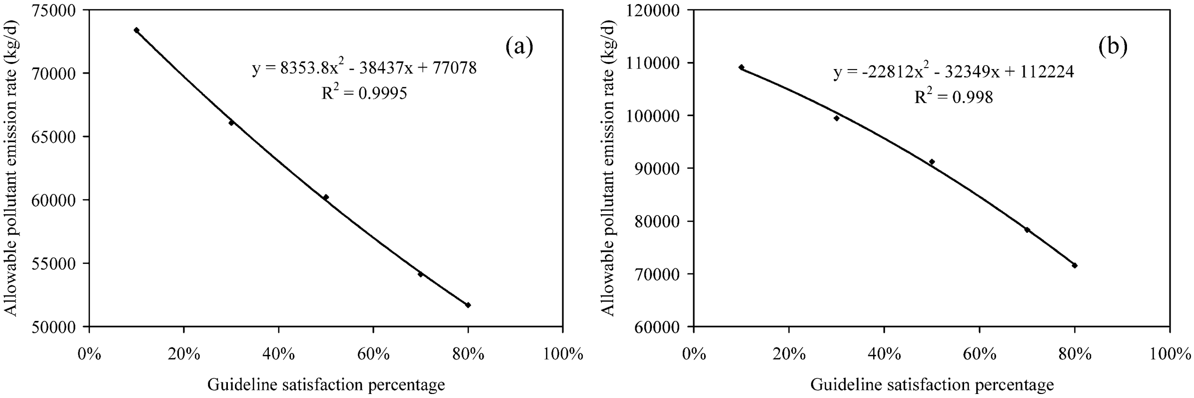

Fig. 6 Regression curve between total allowable SO_2 emission rate and air-quality-guideline satisfaction percentage, (a) heating season, (b) non-heating season.

city is $(51704.50 - 40647.33 - 1076.3 = 9980.87$ kg/d). The AASE of SO_2 for sub-box 2 under the air-quality-guideline satisfaction percentage of 80% is then $(9980.87 \times 25.90\% = 2585.05$ kg/d). The emission reduction objective is calculated as $(7249.76 - 2585.05 = 4664.71$ kg/d) for SO_2. Since the current area-source emission rate of SO_2 is lower than the AASE rate for sub-box 1, 3, 4 and 5, there is no need to reduce the emissions in these sub-boxes. Finally, the emission abatement amount of each pollutant should

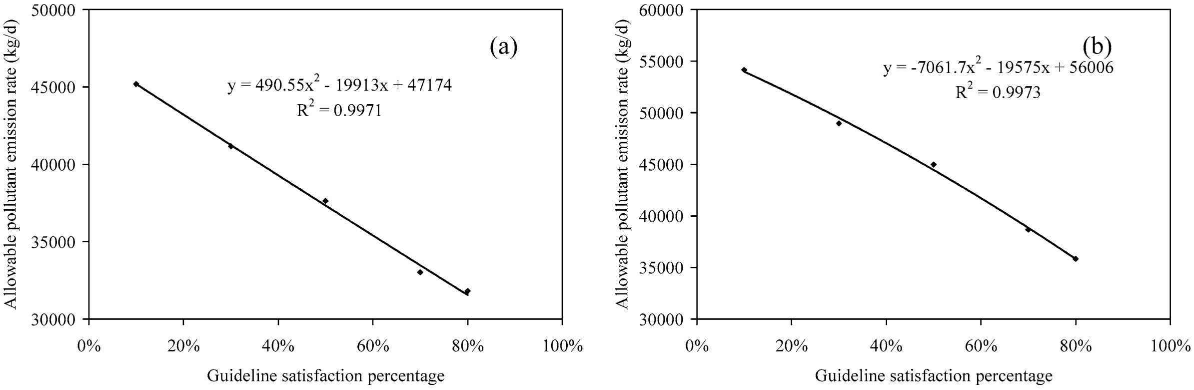

Fig. 7 Regression curve between total allowable PM_{10} emission rate and air-quality-guideline satisfaction percentage, (a) heating season, (b) non-heating season.

Table 5 Area-source emission reduction objectives for each sub-box during the non-heating season

			Calculated AASE rate in each sub-box (kg/d)					
	Date	Wind speed (m/s)	1	2	3	4	5	Total
SO_2	9.24	2.40	6473.14	10878.00	8749.08	19787.34	10653.16	56540.73
	9.25	2.45	6576.82	10592.88	8498.52	20141.58	12685.03	58494.83
	9.26	2.10	5678.26	9495.60	7196.48	17471.82	12787.24	52629.40
	9.27	1.18	2809.78	6186.48	4403.16	10896.78	8449.96	32746.17
	9.28	2.30	4468.66	9988.08	8247.96	20107.02	12450.28	55262.01
	9.29	2.32	5540.02	11353.20	9232.92	18577.74	12018.28	56722.17
	Average		5257.78	9749.04	7721.35	17830.38	11507.33	52065.89
	Ratio ϕ (%)		10.10	18.72	14.83	34.25	22.10	
	Total AASE with η of 80%		30931.46					
	AASE with η of 80%		3124.08	5790.37	4587.14	10594.03	6835.85	
	Existing emission rate		652.49	1448.37	304.37	2183.67	1655.68	
	Emission reduction objective		–	–	–	–	–	
TSP	9.24	2.40	4822.50	9508.15	7378.15	13622.09	7438.07	42768.97
	9.25	2.45	4805.22	9827.83	7525.03	13570.25	7498.55	43226.89
	9.26	2.10	4148.58	9067.51	6635.11	12568.01	6401.27	38820.49
	9.27	1.18	3319.14	6121.27	4941.67	10261.13	7610.87	32254.09
	9.28	2.30	4839.78	9879.67	7741.03	12447.05	5433.59	40341.13
	9.29	2.32	5012.58	10000.63	7352.23	12792.65	5295.35	40453.45
	Average		4491.30	9067.51	6928.87	12543.53	6612.95	39644.17
	Ratio ϕ (%)		11.33	22.87	17.48	31.64	16.68	
	Total AASE with η of 80%		32183.28					
	AASE with η of 80%		3646.37	7360.32	5625.64	10182.79	5368.17	
	Existing emission rate		8454.28	12968.72	9887.23	12624.29	12462.3	56396.82
	Emission reduction objective		4807.91	5608.40	4261.59	2441.50	7094.13	24213.54
PM_{10}	9.24	2.40	1640.07	4147.75	2736.82	5414.67	2380.22	16319.53
	9.25	2.45	1622.79	4113.19	2710.90	5760.27	2527.10	16734.25
	9.26	2.10	1570.95	3646.63	2512.18	4559.31	2354.30	14643.37
	9.27	1.18	1475.91	2246.95	1760.50	3401.55	2501.18	11386.09
	9.28	2.30	2486.79	4000.87	3471.22	5449.23	669.50	16077.61
	9.29	2.32	2547.27	4294.63	3013.30	5094.99	1386.62	16336.81
	Average		1890.63	3741.67	2700.82	4946.67	1969.82	15249.61
	Ratio ϕ (%)		12.40	24.54	17.71	32.44	12.92	
	Total AASE with η of 80%		11221.61					
	AASE with η of 80%		1391.48	2753.78	1987.35	3640.29	1449.83	
	Existing emission rate		4302.7	4460.36	3861.384	4863.424	5267.834	22755.70
	Emission reduction objective		2911.22	1706.58	1874.04	1223.13	3818.00	11532.97

Note: AASE—allowable area-source emission; η—air-quality-guideline satisfaction percentage

be the greater of the emission reduction objectives for each sub-box during the heating and non-heating seasons, in order to keep the air quality at the safe level at both seasons. As a result, the area-source emission reduction objective for each zone of the study city is corresponding to that for the heating season as listed in Table 6. Such objectives are important information for the further emission control system optimization study which will be discussed in the following sections.

4. Optimization of emission reduction

4.1. Overview of optimization approach

After the determination of emission reduction objective in each sub-box, a linear programming model is developed in this study to optimize the emission abatement which is subject to a number of pollution control measures. The economic objective of the air quality management strategy in the study city is to minimize

Table 6 Area-source emission reduction objective for each sub-box during the heating season

			Calculated AASE rate in each sub-box (kg/d)					
	Date	Wind speed (m/s)	1	2	3	4	5	Total
SO_2	12.11	1.13	788.02	2790.96	1906.20	3397.26	1262.95	10145.39
	12.12	1.31	822.58	3067.44	2113.56	3621.90	1332.07	10957.55
	12.13	2.25	986.74	4415.28	2847.96	5453.58	2101.03	15804.59
	12.14	0.94	649.78	1806.00	1206.36	2999.82	2653.99	9315.95
	12.17	1.75	1366.10	3560.48	1428.01	4481.63	2635.01	13471.23
	12.18	1.90	1427.38	3585.84	1431.00	4727.82	3362.47	14534.51
	Average		1006.77	3204.33	1822.18	4113.67	2224.59	12371.54
	Ratio ϕ (%)		8.14	25.90	14.73	33.25	17.98	
	Total AASE with η of 80%		9980.87					
	AASE with η of 80%		812.44	2585.05	1470.18	3318.64	1794.56	
	Existing emission rate		666.26	7249.76	443.05	2338.91	1779.65	
	Emission reduction objective		–	4664.71	–	–	–	
TSP	12.11	1.13	2196.55	5553.25	4091.28	7504.51	4199.97	23545.55
	12.12	1.31	2066.95	6201.25	4151.76	7340.35	3975.33	23735.63
	12.13	2.25	2205.19	5967.97	4341.84	7996.99	4994.85	25506.83
	12.14	0.94	1634.95	5829.73	4246.80	6882.43	3102.69	21696.59
	12.17	1.75	2334.79	5959.33	4359.12	7392.19	5038.05	25083.47
	12.18	1.90	2308.87	5967.97	4367.76	7700.63	5029.41	25374.64
	Average		2124.55	5913.25	4259.76	7469.52	4390.05	24157.12
	Ratio ϕ (%)		8.79	24.48	17.63	30.92	18.17	
	Total AASE with η of 80%		23036.25					
	AASE with η of 80%		2024.88	5638.88	4062.11	7122.93	4186.35	
	Existing emission rate		8669.81	16938.93	10814.66	13589.14	13520.99	63533.53
	Emission reduction objective		6644.93	11300.05	6752.55	6466.21	9334.64	40498.38
PM_{10}	12.11	1.13	1027.17	1629.53	1292.09	2131.58	1072.83	7153.20
	12.12	1.31	1087.65	1690.01	1162.49	2192.06	1185.15	7317.36
	12.13	2.25	1346.85	1569.05	1482.17	3332.54	2636.67	10367.28
	12.14	0.94	785.25	1119.77	1015.61	2243.90	1211.07	6375.60
	12.17	1.75	1165.41	1422.17	1318.01	2788.22	2247.87	8941.68
	12.18	1.90	1191.33	2165.21	1525.37	2572.22	1798.59	9252.72
	Average		1100.61	1599.29	1299.29	2543.42	1692.03	8234.64
	Ratio ϕ (%)		13.37	19.42	15.78	30.89	20.55	
	Total AASE with η of 80%		6917.39					
	AASE with η of 80%		924.86	1343.36	1091.56	2136.78	1421.52	
	Existing emission rate		4375.84	6730.13	4164.44	5235.1	5709.32	26214.83
	Emission reduction objective		3450.98	5386.77	3072.88	3098.32	4287.80	19296.75

Note: AASE—allowable area-source emission; η—air-quality-guideline satisfaction percentage

the total emission control system cost while the environmental objective (e.g. emission reduction objective) can still be satisfied. The general form of an optimization model is as follows:

$$Min\ Z = \sum_{i=1}^{n} C_i X_i \tag{3a}$$

s.t.

$$\sum_{i=1}^{n} A_{ji} X_i \leq B_j \tag{3b}$$

$$X_i \geq 0 \tag{3c}$$

where Z is total cost of emission control by using various measures (RMB ¥/d), X_i is pollutant reduction

Table 7 Treatment cost for various emission control measures for sub-box j

Emission control measure	Treatment cost (¥/t · yr)
$X_{1,j}$ = TSP reduction due to tree planting	C_1 =1327.90
$X_{2,j}$ = TSP reduction due to traffic dust control	$C_2 = 66900.00$
$X_{3,j}$ = TSP reduction due to construction site control	$C_3 = 10760.00$
$X_{4,j}$ = TSP reduction due to storage pile treatment using underground storage warehouse	$C_4 = 5053.69$
$X_{5,j}$ = TSP reduction due to storage pile treatment using covering agent	$C_5 = 2661.19$
$X_{6,j}$ = TSP reduction from industries using bag-house dust filter (BF)	$C_6 = 26.50$
$X_{7,j}$ = TSP reduction from industries using electrostatic precipitator (ESP)	$C_7 = 71.00$
$X_{8,j}$ = TSP reduction from industries using wet scrubber (WS)	$C_8 = 60.00$
$X_{9,j}$ = SO_2 reduction from industries using limestone-gypsum flue gas desulphurization	$C_9 = 1200.0$
$X_{10,j}$ = SO_2 reduction from industries using wet flue gas desulphurization scrubber	$C_{10} = 900.00$
$X_{11,j}$ = SO_2 reduction from industries using spray dryer flue gas desulphurization	$C_{11} = 1100.00$
$X_{12,j}$ = SO_2 reduction from industries using phosphate ammonium fertilizer process (PAFP)	$C_{12} = 1800.00$
$X_{13,j}$ = TSP reduction due to centralized heating	These variables will not be optimized by just using their actual values and costs
$X_{14,j}$ = SO_2 reduction due to centralized heating	
$X_{15,j}$ = TSP reduction due to clean energy utilization	
$X_{16,j}$ = SO_2 reduction due to clean energy utilization	
$X_{17,j}$ = TSP reduction due to relocation of industries	
$X_{18,j}$ = SO_2 reduction due to relocation of industries	

corresponding to emission control measure i (kg/d), C_i is cost of reducing unit mass of pollutant by using control measure i (¥/kg), A_{ji} is the coefficient of the ith control method in the jth constraint, B_j is the jth restriction on pollutant reduction. The environmental objective will be reflected in the constraints.

4.2. Investigation of emission control measures

The possible emission control measures in the study city include (a) planting trees such as pine, fir, cypress, and fast-growing poplar for dust control; (b) reducing traffic dust generation through ordinary road sweeper truck, vacuum road sweeper truck, street sprinkler, and manual sweeping by workers; (c) controlling dust emission from construction sites through enclosures (e.g. brick wall, steel sheet) and use of tarpaulin covers; (d) storage pile treatment through construction of underground storage warehouse and spraying covering agents; (e) area-source dust removal from industries through bag-house filter (BF), electrostatic precipitator (ESP) and wet scrubber (WS); (f) area-source SO_2 removal from industries through limestone-gypsum flue gas desulphurization, wet flue gas desulphurization scrubber, spray dryer flue gas desulphurization, and phosphate ammonium fertilizer desulphurization process (PAFP); (g) dust and SO_2 reduction through centralized heating by establishing coal-fired heat and power plant; (h) dust and SO_2 reduction through clean energy utilization by establishing a warehouse of liquefied petroleum gas, and (i) relocation of industrial enterprises to reduce dust and SO_2 emission. The decision variables of the optimization model will be the pollutant reduction amount due to various emission control measures. However, the emission abatement through control methods (g) to (i) will not be optimized in this study since these three measures have already been proposed by the city government and will be implemented. The unit costs of the above emission control measures were obtained after comprehensive investigation and survey (BUT, 2004). Table 7 lists the related decision variables and estimated cost of different emission control measures for the study city.

4.3. Investigation of constraints

An air-quality-guideline satisfaction percentage of 80% is applied in this paper for the optimization study by consulting with the local government. Thus, the environmental objective of the pollutant emission abatement strategy corresponds to the emission reduction objective during the heating season as listed in Table 6. The constraints in the optimization model (3) imply that the pollutant reduction due to various emission control measures should exceed the emission reduction objectives. In addition, the pollutant emission reduction of each control measure should be restricted by an upper and lower bound due to the specific economic and environmental conditions in each functional zone (e.g. sub-box in the modeling domain). The determination of constraints for the study area will be based on the regulatory documents issued by local government (HPEPB, 2001).Table 8 lists the bounds of tree planting area and pollutant reduction due to tree planting in each functional zone, where the number in the bracket represents the pollutant reduction. For example, (1609.8/559.6) means that the TSP and PM_{10} reduction is 1609.8 and 559.6 kg/d, respectively. The calculation of pollutant reduction is based on the following assumptions: (a) TSP impaction by trees is 11 t/ha·yr; (b) TSP generation from bare grounds is 368.9 g/m^2·yr; (c) PM_{10} impaction by trees is 4 t/ha·yr, and (d) PM_{10} generation from bare grounds is 110.65 g/m^2·yr. For example, when the tree planting area is 40 hectare, the corresponding TSP reduction is calculated as $[(40\,\text{ha}) \times (11\,\text{t/ha·yr}) \times (1000\,\text{kg/t}) + (40\,\text{ha}) \times (368.9\,\text{g/m}^2 \cdot \text{yr}) \times (10000\,\text{m}^2/\text{ha}) \times (10^{-3}\,\text{kg/g}) = 587560\,\text{kg/yr} = 1609.8\,\text{kg/d}]$, and the corresponding PM_{10} reduction is $[(40\,\text{ha}) \times (4\,\text{t/ha·yr}) \times (1000\,\text{kg/t}) + (40\,\text{ha}) \times (110.65\,\text{g/m}^2 \cdot \text{yr}) \times (10000\,\text{m}^2/\text{ha}) \times (10^{-3}\,\text{kg/g}) = 204260\,\text{kg/yr} = 559.6\,\text{kg/d}]$.

In terms of the constraints on traffic dust control, the pollutant reduction efficiency is estimated to be 60% to 90% of the current dust emission for sub-box 1 to 4 due to the application of sweeping trucks. For sub-box 5, the emission reduction efficiency is estimated to be 48% to 72% since this functional zone is not the focus of future urban development and it is difficult to implement daily sweeping of the traffic dust. In terms of the construction site dust control, the pollutant reduction efficiency is estimated to be 40% to 80% of the current dust emission for sub-box 1 to 4, and 50% to 70% for sub-box 5. In terms of dust control for storage piles, the big storage piles currently existing in sub-box 1, 4 and 5 could be treated by establishing underground warehouses which have a pollutant reduction efficiency of at least 90%; the treatment of other medium- and small-sized storage piles using enclosures or spraying covering agents is estimated to have a reduction efficiency of at least 50%. In addition, the pollutant emission from residential self heating could be eliminated by using centralized heating provided by the Fengnan Thermal Power Plant; the pollutant emission from restaurant could be eliminated by substituting coal with clean energy (e.g. liquefied petroleum gas). In terms of the area-source emission (e.g. with stack height lower than 35 m) from industries, the control measures vary for different enterprises in each sub-box, and the estimated pollutant reduction should be constrained according to the practical situations in the study city (e.g. some enterprises will be relocated out of sub-box 2 and 3 according to the government's requirement) (BUT, 2004). Consequently,Table 9 lists the lower and upper bounds of emission reduction due to various control measures for the area sources in each sub-box.

4.4. Optimization model development

The pollutant emission reduction through control methods (a) to (f) described in section 4.2 will be optimized in this study. According to Table 6, the reduction of TSP and PM_{10} should be optimized for each sub-box,

Table 8 Constraints for pollutant reduction due to tree planting for each sub-box (unit: kg/d)

Sub-box	Lower bound of tree planting area and pollutant reduction (TSP/PM_{10})	Upper bound of tree planting area and pollutant reduction (TSP/PM_{10})
1	40 ha (1609.8/559.6)	60 ha (2414.4/839.4)
2	25 ha (1006/349.75)	80 ha (3219.2/1119.2)
3	12 ha (482.88/167.88)	80 ha (3219.2/1119.2)
4	45 ha (1810.8/629.55)	80 ha (3219.2/1119.2)
5	10 ha (402.4/139.9)	80 ha (3219.2/1119.2)

while the SO_2 reduction only needs to be optimized for sub-box 2. The objective function of this optimization problem for sub-box j can then be described as follows:

$$\begin{aligned} Min \quad Z_j &= C_1X_{1,j} + C_2X_{2,j} + C_3X_{3,j} + C_4X_{4,j} \\ &+ C_5X_{5,j} + C_6X_{6,j} + C_7X_{7,j} + C_8X_{8,j} \\ &+ C_9X_{9,j} + C_{10}X_{10,j} + C_{11}X_{11,j} + C_{12}X_{12,j} \quad (4) \end{aligned}$$

where $X_{1,j}$ to $X_{12,j}$ are decision variables (e.g. pollutant reduction) for sub-box j ($j = 1, 2, \ldots, 5$), and C_1 to C_{12} are the corresponding treatment costs for various emission control measures as listed in Table 7.

The constraints of model (4) should be established for each sub-box due to its unique conditions. In addition, the proportion of PM_{10} in TSP from various emission sources should be known so that the constraints for PM_{10} can be established. In this study, the average proportion of PM_{10} in TSP is estimated to be 27% for bare ground dust, 35% for traffic dust, 22% for construction site dust, 22% for storage pile dust, 70% for industrial dust (mainly from iron and steel and cement industries), 77% for coal-fired boiler dust, and 68% for dust due to residential heating, respectively.

4.4.1. Constraints for Sub-Box 1

The constraints for TSP can be described as follows:

$$\begin{aligned} &X_{1,1} + X_{2,1} + X_{3,1} + X_{4,1} + X_{5,1} + X_{6,1} + X_{7,1} \\ &+X_{8,1} \geq 6644.93 - 48.73 - 47.48 = 6548.72 \quad (5a) \end{aligned}$$

$$X_{6,1} + X_{7,1} + X_{8,1} \leq 3856.96 \quad (5b)$$

$$1609.8 \leq X_{1,1} \leq 2414.4 \quad (5c)$$

$$435.55 \leq X_{2,1} \leq 653.32 \quad (5d)$$

$$284.47 \leq X_{3,1} \leq 568.94 \quad (5e)$$

$$80.13 \leq X_{4,1} \leq 89.03 \quad (5f)$$

$$164.31 \leq X_{5,1} \leq 328.61 \quad (5g)$$

$$0 \leq X_{6,1} \leq 3856.96 \quad (5h)$$

$$0 \leq X_{7,1} \quad (5i)$$

$$0 \leq X_{8,1} \quad (5j)$$

The constraints for PM_{10} are described as:

$$\begin{aligned} &0.27X_{1,1} + 0.35X_{2,1} + 0.22X_{3,1} + 0.22X_{4,1} + 0.22X_{5,1} \\ &+0.70X_{6,1} + 0.70X_{7,1} + 0.70X_{8,1} \geq 3450.98 - 66.98 \\ &= 3384 \quad (5k) \end{aligned}$$

$$0.70X_{6,1}+0.70X_{7,1}+0.70X_{8,1} \leq 2588.48 \quad (5l)$$

$$559.6 \leq 0.35X_{1,1} \leq 839.4 \Leftrightarrow 1598.85 \leq X_{1,1} \leq 3108.88 \quad (5m)$$

$$147.65 \leq 0.35X_{2,1} \leq 221.47 \Leftrightarrow 421.85 \leq X_{2,1} \leq 632.77 \quad (5n)$$

$$67.13 \leq 0.22X_{3,1} \leq 134.26 \Leftrightarrow 305.13 \leq X_{3,1} \leq 610.27 \quad (5o)$$

$$19.56 \leq 0.22X_{4,1} \leq 22.25 \Leftrightarrow 79.72 \leq X_{4,1} \leq 101.36 \quad (5p)$$

$$23.91 \leq 0.22X_{5,1} \leq 47.81 \Leftrightarrow 108.63 \leq X_{5,1} \leq 217.31 \quad (5q)$$

4.4.2. Constraints for Sub-Box 2

The constraints for TSP can be described as follows:

$$\begin{aligned} &X_{1,2} + X_{2,2} + X_{3,2} + X_{4,2} + X_{5,2} + X_{6,2} + X_{7,2} + X_{8,2} \\ &\geq 11300.05 - 4332.77 - 781.49 - 967.46 = 5218.33 \quad (6a) \end{aligned}$$

$$X_{6,2}+X_{7,2}+X_{8,2} \leq 151.18 \quad (6b)$$

$$1006 \leq X_{1,2} \leq 3219.2 \quad (6c)$$

$$2227.43 \leq X_{2,2} \leq 3341.15 \quad (6d)$$

$$327.33 \leq X_{3,2} \leq 654.66 \quad (6e)$$

$$176.70 \leq X_{5,2} \leq 318.05 \quad (6f)$$

$$0 = X_{6,2} \quad (6g)$$

$$0 \leq X_{8,2} \leq 151.18 \quad (6h)$$

$$0 = X_{7,2} \quad (6i)$$

The constraints for PM_{10} are described as:

$$\begin{aligned} &0.27X_{1,2} + 0.35X_{2,2} + 0.22X_{3,2} + 0.22X_{4,2} + 0.22X_{5,2} \\ &+0.70X_{6,2} + 0.70X_{7,2} + 0.70X_{8,2} \geq 5386.77 - 2832.94 \\ &-439.66 - 677.22 = 1436.95 \quad (6j) \end{aligned}$$

$$0 \leq 0.70X_{6,2} + 0.70X_{7,2} + 0.70X_{8,2} \leq 97.97 \quad (6k)$$

$$349.75 \leq 0.27X_{1,2} \leq 1119.2 \Leftrightarrow 1295.37 \leq X_{1,2} \leq 4145.18 \quad (6l)$$

$$633.07 \leq 0.35X_{2,2} \leq 949.61 \Leftrightarrow 2344.70 \leq X_{2,2} \leq 3517.07 \quad (6m)$$

$$77.59 \leq 0.22X_{3,2} \leq 155.18 \Leftrightarrow 352.68 \leq X_{3,2} \leq 705.36 \quad (6n)$$

$$44.17 \leq 0.22X_{5,2} \leq 79.51 \Leftrightarrow 200.77 \leq X_{5,2} \leq 361.41 \quad (6o)$$

$$0 \leq 0.70X_{8,2} \leq 97.97 \Leftrightarrow 0 \leq X_{8,2} \leq 140.00 \quad (6p)$$

The constraints for SO_2 are described as:

$$\begin{aligned} X_{9,2} + X_{10,2} + X_{11,2} + X_{12,2} &\geq 4664.71 - 5811.39 \\ &- 742.26 - 240.31 = -2129.25 \quad (6q) \end{aligned}$$

$$0 \leq X_{9,2} \quad (6r)$$

$$0 \leq X_{10,2} \quad (6s)$$

$$0 \leq X_{11,2} \tag{6t}$$

$$0 \leq X_{12,2} \tag{6u}$$

4.4.3. Constraints for Sub-Box 3

The constraints for TSP can be described as follows:

$$\begin{aligned} &X_{1,3} + X_{2,3} + X_{3,3} + X_{5,3} + X_{6,3} + X_{7,3} + X_{8,3} \\ &\geq 6752.55 - 540.74 - 2.30 - 1932.39 = 4277.12 \end{aligned} \tag{7a}$$

$$X_{6,3}+X_{7,3}+X_{8,3} \leq 263.72 \tag{7b}$$

$$482.88 \leq X_{1,3} \leq 3219.2 \tag{7c}$$

$$1432.22 \leq X_{2,3} \leq 2148.33 \tag{7d}$$

$$392.73 \leq X_{3,3} \leq 785.46 \tag{7e}$$

$$112.60 \leq X_{5,3} \leq 202.67 \tag{7f}$$

$$0 = X_{6,3} \tag{7g}$$

$$0 \leq X_{7,3} \leq 263.72 \tag{7h}$$

$$0 = X_{8,3} \tag{7i}$$

The constraints for PM$_{10}$ are described as:

$$\begin{aligned} &0.27X_{1,3} + 0.35X_{2,3} + 0.22X_{3,3} + 0.22X_{5,3} + 0.70X_{6,3} \\ &+0.70X_{7,3} \geq 3072.88 - 378.52 - 1.59 - 1402.03 \\ &= 1290.74 \end{aligned} \tag{7j}$$

$$0 \leq 0.70X_{6,3} + 0.70X_{7,3} + 0.70X_{8,3} \leq 157.33 \tag{7k}$$

$$167.88 \leq 0.27X_{1,3} \leq 1119.2 \Leftrightarrow 621.77 \leq X_{1,3} \leq 4145.18 \tag{7l}$$

$$485.52 \leq 0.35X_{2,3} \leq 728.28 \Leftrightarrow 1387.2 \leq X_{2,3} \leq 2080.8 \tag{7m}$$

$$92.68 \leq 0.22X_{3,3} \leq 185.36 \Leftrightarrow 421.27 \leq X_{3,3} \leq 842.54 \tag{7n}$$

$$28.36 \leq 0.22X_{5,3} \leq 45.38 \Leftrightarrow 128.9 \leq X_{5,3} \leq 206.27 \tag{7o}$$

$$0 \leq 0.70X_{6,3} \Leftrightarrow 0 \leq X_{6,3} \tag{7p}$$

$$0 \leq 0.70X_{7,3} \leq 157.44 \Leftrightarrow 0 \leq X_{7,3} \leq 224.80 \tag{7q}$$

$$0 \leq 0.70X_{8,3} \Leftrightarrow 0 \leq X_{8,3} \tag{7r}$$

4.4.4. Constraints for Sub-Box 4

The constraints for TSP can be described as follows:

$$\begin{aligned} &X_{1,4} + X_{2,4} + X_{3,4} + X_{4,4} + X_{5,4} + X_{6,4} + X_{7,4} \\ &+X_{8,4} \geq 6466.21 - 1055.92 = 5410.29 \end{aligned} \tag{8a}$$

$$0 \leq X_{6,4} + X_{7,4} + X_{8,4} \leq 2193.31 \tag{8b}$$

$$1810.8 \leq X_{1,4} \leq 3219.2 \tag{8c}$$

$$2025.88 \leq X_{2,4} \leq 3038.82 \tag{8d}$$

$$562.35 \leq X_{3,4} \leq 1124.7 \tag{8e}$$

$$87.49 \leq X_{4,4} \leq 97.22 \tag{8f}$$

$$293.12 \leq X_{5,4} \leq 586.24 \tag{8g}$$

$$0 \leq X_{6,4} \leq 1893.10 \tag{8h}$$

$$0 \leq X_{7,4} \leq 1893.10 \tag{8i}$$

$$0 \leq X_{8,4} \leq 300.21 \tag{8j}$$

The constraints for PM$_{10}$ are described as:

$$\begin{aligned} &0.27X_{1,4} + 0.35X_{2,4} + 0.22X_{3,4}+0.22X_{4,4} + 0.22X_{5,4} \\ &+0.70X_{6,4} + 0.70X_{7,4} + 0.70X_{8,4} \geq 3098.32 - 760.14 \\ &= 2338.18 \end{aligned} \tag{8k}$$

$$0 \leq 0.70X_{6,4} + 0.70X_{7,4} + 0.70X_{8,4} \leq 1677.48 \tag{8l}$$

$$629.55 \leq 0.27X_{1,4} \leq 1119.2 \Leftrightarrow 2331.66 \leq X_{1,4} \leq 4145.18 \tag{8m}$$

$$477.37 \leq 0.35X_{2,4} \leq 716.06 \Leftrightarrow 1363.91 \leq X_{2,4} \leq 2045.88 \tag{8n}$$

$$117.16 \leq 0.22X_{3,4} \leq 234.32 \Leftrightarrow 532.54 \leq X_{3,4} \leq 1065.09 \tag{8o}$$

$$21.87 \leq 0.22X_{4,4} \leq 24.30 \Leftrightarrow 87.31 \leq X_{4,4} \leq 110.45 \tag{8p}$$

$$43.48 \leq 0.22X_{5,4} \leq 86.96 \Leftrightarrow 197.63 \leq X_{5,4} \leq 395.27 \tag{8q}$$

$$0 \leq 0.70X_{6,4} \leq 1491.86 \Leftrightarrow 0 \leq X_{6,4} \leq 1131.23 \tag{8r}$$

$$0 \leq 0.70X_{7,4} \leq 1491.86 \Leftrightarrow 0 \leq X_{7,4} \leq 1131.23 \tag{8s}$$

$$0 \leq 0.70X_{8,4} \leq 185.62 \Leftrightarrow 0 \leq X_{8,4} \leq 265.17 \tag{8t}$$

4.4.5. Constraints for Sub-Box 5

The constraints for TSP can be described as follows:

$$\begin{aligned} &X_{1,5} + X_{2,5} + X_{3,5} + X_{4,5} + X_{5,5} + X_{6,5} + X_{7,5} + X_{8,5} \\ &\geq 9334.64 - 771.67 = 8562.97 \end{aligned} \tag{9a}$$

$$0 \leq X_{6,5} + X_{7,5} + X_{8,5} \leq 2149.89 + 1382.73 = 3532.62 \tag{9b}$$

$$402.4 \leq X_{1,5} \leq 3219.2 \tag{9c}$$

$$1503.58 \leq X_{2,5} \leq 2255.37 \tag{9d}$$

$$670.28 \leq X_{3,5} \leq 938.39 \tag{9e}$$

$$28.96 \leq X_{4,5} \leq 32.18 \tag{9f}$$

$$262.46 \leq X_{5,5} \leq 524.93 \tag{9g}$$

$$0 \leq X_{6,5} \leq 2149.89 \tag{9h}$$

Table 9 Lower and upper bounds of emission reduction from various area sources in each sub-box (unit: kg/d)

		Current emission			Bounds of pollutant reduction		
	Source	TSP	PM_{10}	SO_2	TSP	PM_{10}	SO_2
1	Bare ground	1668.03	390.32		[1609.8, 2414.4]	[559.6, 839.4]	
	Traffic dust	725.91	246.08		[435.55, 653.32]	[147.65, 221.47]	
	Construction site	711.18	167.83		[284.47, 568.94]	[67.13, 134.26]	
	Big storage piles	89.03	22.25		[80.13, 89.03]	[17.54, 22.25]	
	Other storage piles	328.61	47.81		[164.31, 328.61]	[23.91, 47.81]	
	Industries relocation	0	0	0	0	0	0
	Industries pollution control[a]	5050.84	3434.57	621.47	[0, 3856.96]	[0, 2588.48]	0
	Residential self heating[b]	48.73	34.11	13.77	48.73	34.11	13.77
	Restaurant[c]	47.48	32.87	31.02	47.48	32.87	31.02
2	Bare ground	5368.37	1051.01		[1006.0, 3219.2]	[349.75, 1119.2]	
	Traffic dust	3712.39	1055.12		[2227.43, 3341.15]	[633.07, 949.61]	
	Construction site	818.33	193.98		[327.33, 654.66]	[77.59, 155.18]	
	Storage piles	353.39	88.34		[176.70, 318.05]	[44.17, 79.51]	
	Industries relocation	967.46	677.22	240.31	967.46	677.22	240.31
	Industries pollution control[d]	604.72	391.86	465.80	[0, 151.18]	[0, 97.97]	[0, 46.5]
	Residential self heating[b]	4332.77	2832.94	5811.39	4332.77	2832.94	5811.39
	Restaurant[c]	781.49	439.66	742.26	781.49	439.66	742.26
3	Bare ground	3690.31	863.53		[482.88, 3219.2]	[167.88, 1119.2]	
	Traffic dust	2387.03	809.20		[1432.22, 2148.33]	[485.52, 728.28]	
	Construction site	981.82	231.70		[392.73, 785.46]	[92.68, 185.36]	
	Storage piles	225.19	56.73		[112.60, 202.67]	[28.36, 45.38]	
	Industries relocation	1932.39	1402.03	107.40	1932.39	1402.03	107.40
	Industries pollution control[a]	1054.88	629.04	38.07	[0, 263.72]	[0, 157.33]	0
	Residential self heating[b]	540.74	378.52	291.31	540.74	378.52	291.31
	Restaurant[c]	2.30	1.59	6.27	2.30	1.59	6.27
4	Bare ground	3431.55	802.98		[1810.8, 3219.2]	[629.55, 1119.2]	
	Traffic dust	3376.47	795.62		[2025.88, 3038.82]	[477.37, 716.06]	
	Construction site	1405.87	292.90		[562.35, 1124.70]	[117.16, 234.32]	
	Big storage piles	97.22	24.30		[87.49, 97.22]	[19.21, 24.30]	
	Other storage piles	586.24	86.96		[293.12, 586.24]	[43.48, 86.96]	
	Industries relocation	0	0	0	0	0	0
	Industries pollution control	9207.77	6094.12	31402.86	[0, 1893.1][e]	[0, 1491.86][e]	0
					[0, 300.21][d]	[0, 185.62][d]	0
	Residential self heating[b]	1055.92	760.14	596.44	1055.92	760.14	596.44
	Restaurant[c]	0	0	0	0	0	0
5	Bare ground	3199.04	748.58		[402.4, 3219.2]	[139.9, 1119.2]	
	Traffic dust	3132.46	1061.90		[1503.58, 2255.37]	[509.71, 764.57]	
	Construction site	1340.56	316.37		[670.28, 938.39]	[158.18, 221.45]	
	Big storage piles	32.18	8.05		[28.96, 32.18]	[6.35, 8.05]	
	Other storage piles	524.93	124.02		[262.46, 524.93]	[62.01, 124.02]	
	Industries relocation	0	0	0	0	0	0
	Industries pollution control	4520.15	3073.70	1370.47	[0, 2149.89][e]	[0, 1475.22][e]	0
					[0, 1382.73][d]	[0, 926.96][d]	0
	Residential self heating[b]	649.00	454.30	274.52	649.00	454.30	274.52
	Restaurant[c]	122.67	84.93	134.92	122.67	84.93	134.92

Note: a—the dust removal measure is to use bag-house filters; b—the pollution control measure is to use centralized heating; c—the pollution control measure is to use clean energy; d—the dust removal measure is to use wet scrubbers; e—the dust removal measure is to use bag-house filters and electrostatic precipitators

$$0 \le X_{7,5} \le 2149.89 \tag{9i}$$

$$0 \le X_{8,5} \le 1382.73 \tag{9j}$$

The constraints for PM_{10} are described as:

$$0.27X_{1,5} + 0.35X_{2,5} + 0.22X_{3,5} + 0.22X_{4,5} + 0.22X_{5,5} + 0.70X_{6,5}$$

$$+0.70X_{7,5} + 0.70X_{8,5} \ge 4287.80 - 539.23 = 3748.57 \tag{9k}$$

$$0.70X_{6,5} + 0.70X_{7,5} + 0.70X_{8,5} \le 1475.22 + 926.96$$

$$= 2402.18 \tag{9l}$$

$$139.9 \le 0.27X_{1,5} \le 1119.2 \Leftrightarrow 518.15 \le X_{1,5} \le 4145.18 \tag{9m}$$

$$509.71 \le 0.35X_{2,5} \le 764.57 \Leftrightarrow 1456.31 \le X_{2,5} \le 2184.48 \tag{9n}$$

$$158.18 \le 0.22X_{3,5} \le 221.45 \Leftrightarrow 719.0 \le X_{3,5} \le 1006.59 \tag{9o}$$

$$6.35 \le 0.22X_{4,5} \le 8.05 \Leftrightarrow 28.86 \le X_{4,5} \le 36.50 \tag{9p}$$

$$62.01 \le 0.22X_{5,5} \le 124.02 \Leftrightarrow 281.86 \le X_{5,5} \le 563.72 \tag{9q}$$

$$0 \le 0.70X_{6,5} \le 1475.22 \Leftrightarrow 0 \le X_{6,5} \le 2107.45 \tag{9r}$$

$$0 \le 0.70X_{7,5} \le 1475.22 \Leftrightarrow 0 \le X_{7,5} \le 2107.45 \tag{9s}$$

$$0 \le 0.70X_{8,5} \le 926.96 \Leftrightarrow 0 \le X_{8,5} \le 1324.23 \tag{9t}$$

5. Analysis and discussion of optimal emission abatement

The optimal pollutant reduction using various emission control measures can then be obtained by solving the above optimization models for each sub-box. Table 10 lists the corresponding results. It is found that the optimal TSP reduction through tree planting measure (e.g. X_1) is within the interval of possible pollutant reduction in each sub-box through this measure since the tree planting is associated with intermediate unit treatment cost (e.g. ￥1327.90/t.yr); the optimal TSP reduction through traffic dust control measure (e.g. X_2) is nearly equal to the lower bound of the possible pollutant reduction interval in each sub-box since the traffic dust control measure is associated with the highest unit treatment cost (e.g. ￥66900.0/t.yr). For example, the optimal TSP reduction through traffic dust control measure is 435.55 kg/d for sub-box 1 while the possible TSP reduction in this sub-box is within [435.55, 653.32] kg/d. The optimal TSP reductions through construction site dust control and storage pile treatment measures (e.g. X_3, X_4 and X_5) are close to the lower bound of the possible pollutant reduction intervals in each sub-box since these two emission control measures are associated

Table 10 Optimal pollutant reduction by using various emission control measures (unit: kg/d)

	Sub-box					
Decision variables	1	2	3	4	5	Total
X_1	1934.00	2180.20	2069.50	2331.70	2358.10	10873.50
X_2	435.55	2344.70	1432.22	2025.90	1503.60	7741.90
X_3	305.10	352.70	421.80	562.40	719.00	2361.00
X_4	80.10	0	0	87.50	29.00	196.60
X_5	164.30	200.80	128.90	293.10	281.90	1069.00
X_6	3697.80	0	224.80	1131.23	2107.40	7161.23
X_7	0	0	0	0	637.10	637.10
X_8	0	140.00	0	265.17	927.00	1332.17
X_9	0	0	0	0	0	0
X_{10}	0	0	0	0	0	0
X_{11}	0	0	0	0	0	0
X_{12}	0	0	0	0	0	0
$X13^{*}$	48.73	4332.77	540.74	1055.92	649.00	6627.16
$X14^{*}$	13.77	5811.39	291.31	596.44	274.52	6987.43
$X15^{*}$	47.48	781.49	2.30	0	122.67	953.94
$X16^{*}$	31.02	742.26	6.27	0	134.92	914.47
$X17^{*}$	0	967.46	1932.39	0	0	2899.85
$X18^{*}$	0	240.31	107.40	0	0	347.71
Total TSP reduction	6713.01	11300.12	6752.64	7752.92	9334.77	41853.45
Total SO_2 reduction	44.79	6793.96	404.98	596.44	409.44	8249.61

Note: *—the emission reduction through centralized heating, clean energy utilization and relocation of industries is equal to its corresponding actual value without optimization.

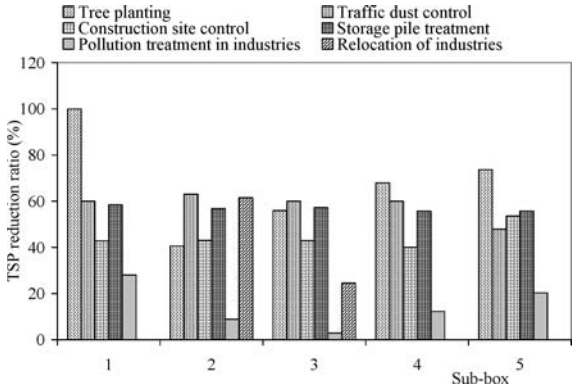

Fig. 8 TSP reduction ratio under various emission control measures for each sub-box.

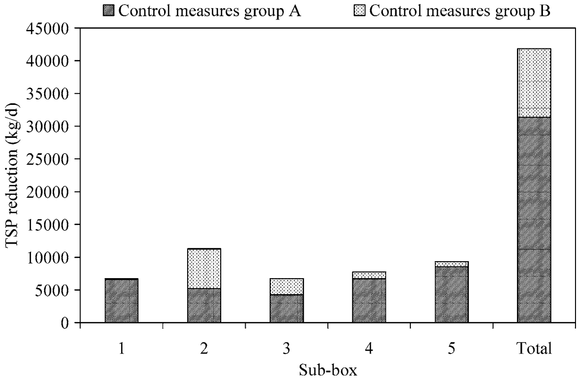

Fig. 9 TSP reduction comparison between optimal control measures (measures group A) and non-optimal control measures (measures group B).

with relatively high unit treatment costs (e.g. ¥10760.0/t.yr, ¥5053.69/t.yr, and ¥2661.19/t.yr); the optimal TSP reduction from industries in each sub-box through bag-house filter (BF), electrostatic precipitator (ESP) and wet scrubber (WS) (e.g. X_6, X_7 and X_8) is close to the upper bound of the possible pollutant reduction interval due to the relatively low unit treatment costs of these industrial emission control measures (e.g. ¥26.5/t.yr, ¥71.0/t.yr, and ¥60.0/t.yr). For example, the optimal TSP reduction through BF, ESP and ES emission control measures is 3697.80 kg/d for sub-box 1 while the possible TSP reduction interval is [0,3856.96] kg/d.

Fig. 8presents the TSP reduction ratio under various emission control measures, where the ratio is equal to the optimal reduction divided by the current pollutant emission. It is found from Fig. 8 that each dust control measure has varied efficiency in pollutant reduction while satisfying the related constraints. In terms of tree planting, it has a significant efficiency to reduce TSP, due to the fact that the restriction of dust emission from bare grounds by vegetation and the impaction and absorption of atmospheric dust by trees. The tree planting has the highest TSP reduction in sub-box 1 as compared to other four sub-boxes. This is because that sub-box 1 includes more emission sources close to the residential area which requires more tree-planting. In sub-box 2, the TSP reduction from industries is high due to the relocation of heavily-polluted industries out of this zone. In terms of SO_2 reduction, it is only necessary to optimize for sub-box 2 (see Table 6), and there is no need to reduce SO_2 emission in other sub-boxes. Since the SO_2 abatement through centralized heating can satisfy the related reduction objective in sub-box 2, the optimal SO_2 reduction from industrial area sources is zero as shown in Table 10. It is observed from the monitoring results that the SO_2 concentration is significantly below the air quality standard in the non-heating season, but there is severe SO_2 pollution during the heating season. This situation is due to the emissions from large amounts of low-height area sources which combust coal for winter residential heating. After the implementation of centralized heating, such area sources could be eliminated to meet the total allowable emission requirement. However, the industries in the study city still need to improve their manufacturing process and strengthen current pollution control efforts to reduce SO_2 emission in order to preserve the air quality at a safe level.Fig. 9 presents the TSP reduction comparison between optimal control measures and non-optimal control measures, where the control measures group A in the figure refers to the dust emission control measures (a) to (e) described in section 4.2, and control measures group B means the emission control methods (g) to (i). In this study, only the emission reductions through control measure group A were optimized, resulting in optimal control measures, while the non-optimal measures mean those contained in control measure group B. It is found from this figure that centralized heating has a significant impact on reducing TSP of sub-box 2 which is a combination area of industrial, residential, cultural and educational activities. The costs of various emission control measures associated with the above obtained optimization results are listed inTable 11. Considering a survival rate of 85% for the planted trees, the total cost of purchasing trees for planting would be ¥1890.09 × 10^4.

Table 11 Cost of optimal emission control alternatives

	Emission control alternatives		Sub-box					Total
			1	2	3	4	5	
A	TSP reduction (kg/d)		1934.00	2180.20	2069.50	2331.70	2358.10	10873.50
	Tree planting area (ha)		48	55	52	58	59	272
	Cost of purchasing (¥10,000)		283.51	324.86	307.14	342.58	348.49	1606.58
	Cost of annual maintenance (¥10,000)		51.21	58.68	55.48	61.88	62.95	290.20
B	Dust reduction	(kg/d)	305.10	352.70	421.30	562.40	719.00	2216.70
		(t/a)	111.36	128.74	153.77	205.28	262.43	809.10
	Annual cost (¥10,000/yr)		119.82	138.52	165.46	220.88	225.90	870.58
C	Underground storage warehouse	TSP reduction (kg/d)	80.10	0	0	87.50	29.00	196.60
		TSP reduction (t/yr)	28.84	0	0	31.50	10.44	70.78
		Cost (¥10,000)	218.62	0	0	238.79	79.14	536.54
	Spraying covering agent	TSP reduction (kg/d)	164.30	200.80	128.90	293.10	281.90	1069.00
		TSP reduction (t/yr)	59.15	72.29	46.40	105.52	101.48	384.82
		Cost (¥10,000)	15.74	19.24	12.35	28.08	27.01	102.38
	BF	TSP reduction (kg/d)	3697.80	0	224.80	1131.23	2107.40	7161.23
		TSP reduction (t/yr)	1331.21	0	80.93	407.24	758.66	2578.04
		Equipment cost (¥10,000)	1959.00	0	12.60	2552.00	510.00	5033.60
		Total investment (¥10,000)	3265.00	0	31.50	4253.00	1275.00	8824.50
		Operational cost (¥10,000/yr)	220.00	0	3.15	67.25	12.75	303.15
D	ESP	TSP reduction (kg/d)	0	0	0	0	229.36	229.36
		TSP reduction (t/yr)	0	0	0	0	82.56	82.56
		Equipment cost (¥10,000)	0	0	0	925.30	270.00	1195.30
		Total investment (¥10,000)	0	0	0	1850.60	540.00	2390.60
		Operational cost (¥10,000/yr)	0	0	0	616.90	180.00	796.90

(Continued on next page)

Table 11 *(Continued)*

Emission control alternatives		Sub-box					Total
		1	2	3	4	5	
WS	TSP reduction (kg/d)	0	140.00	0	265.17	927.00	1332.17
	TSP reduction (t/yr)	0	50.40	0	95.46	333.72	479.58
	Equipment cost (¥10,000)	0	15.00	0	28.00	104.00	147.00
	Total investment (¥10,000)	0	37.50	0	70.00	260.00	367.50
	Operational cost (¥10,000/yr)	0	39.00	0	72.80	270.40	121.28
	Total investment for industrial pollution control (¥10,000)						11582.6
	Annual operational cost for industrial pollution control (¥10,000/yr)						1221.33

	Sweeping measure	Sweeping capacity	Ratio (%)	Number of sweeping trucks or workers	Cost of purchasing (¥10,000)	Annual maintenance (¥10,000)
E	Ordinary road sweeper	$15000\,\mathrm{m^2/h} \cdot$ truck	40	7	70.0	16.8
	Vacuum road sweeper	$40000\,\mathrm{m^2/h} \cdot$ truck	30	2	80.0	14.72
	Road sprinkler	$15000\,\mathrm{m^2/h} \cdot$ truck	20	4	48.0	16.08
	Manual sweeping	$600\,\mathrm{m^2/h} \cdot$ worker	10	45		27.0
		Sub-total			198.0	74.6

Note: A—tree planting, B—construction site dust control, C—storage pile dust control, D—industries pollution control, BF—baghouse filter, ESP—electrostatic precipitator, WS—wet scrubber

Among the optimized emission control costs, the local government should be responsible for the cost of tree planting, traffic dust control, centralized heating and establishing the warehouse for liquefied petroleum gas (1500 t/yr). The related industries should take care of the cost for construction site dust control, establishing underground material storage warehouse, spraying covering agent for the storage piles, dust control in the industries, and relocation of heavily-polluted industries.

The Fengnan district is an industrial city which heavily depends on coal combustion, and its air quality is also affected by the neighboring cities which are associated with air pollution problems. It is observed from the monitoring program that there is a relatively high pollutant inflow concentration from the boundary of the study city. For example, the TSP inflow concentrations from the east and north wind-direction-group during the heating season are 0.34 and $0.31\,\mathrm{mg/m^3}$, respectively, which exceed the air quality standard. Thus the improvement of air quality in Fengnan district should also be linked with the emission control efforts in the neighboring cities. Although the optimal emission control measures have been achieved in this study as listed in Table 10, there are still a number of uncertainties associated with the air quality improvement through area-source emission abatement. For example, the effect of tree planting in the urban area on dust restriction will not be realized until a period of time (e.g. after the trees grow big enough); the ordinary road sweeping method may generate suspended particulate matter causing secondary pollution as compared to the vacuum road sweeping method; the current construction of thermal power plant and the related pipes will generate dust pollution and have adverse impacts on the urban air quality, and this construction project is estimated to be completed within 2007 and 2010. As a result, there is still difficulty in meeting the air-quality-guideline satisfaction percentage of 80% in 2007 even though the optimal measures have been implemented. However, it is realistic that the air quality may reach this desired objective in 2010 after the emission control measures have been steadily strengthened. This paper presented a linear programming model to optimize the emission control measures based on the Gaussian-box modeling system for air quality prediction. However, many uncertainties may be associated with various modeling inputs and optimization parameters as well as the emissions (Liu *et al.*, 2003). Although these inputs and parameters were obtained through comprehensive statistical analysis and survey in this study, and the pollutant reductions were restricted within the lower and upper bounds by considering uncertainties in pollutant removal efficiencies of various control measures, such uncertainties still need to be effectively incorporated into the modeling system (e.g. development of stochastic and/or fuzzy programming model) in future studies to obtain more robust solutions.

6. Conclusions

A modeling framework by linking air quality simulation with system optimization was presented in this paper to develop cost-effective urban air quality management strategies in the Fengnan district of China. The contributions of various emission sources to the air quality (characterized by daily average concentrations of SO_2, TSP and PM_{10}) during the heating and non-heating seasons were quantified using the Gaussian-box modeling system. The relation between the total allowable emission and wind speed as well as the relation between the total allowable emission and air-quality-guideline satisfaction were quantified based on the simulation results. The area-source emission reduction objective in each sub-box of the modeling domain during the heating and non-heating seasons was then calculated. A linear programming model was developed to optimize the emission abatement which was subject to a number of pollution control measures in the study city. The emission control measures need to be optimized included (a) planting trees for dust control; (b) reducing traffic dust generation through various road sweeper trucks and manual sweeping; (c) controlling dust emission from construction sites through enclosures; (d) storage pile treatment through construction of underground storage warehouse and spraying covering agents; (e) area-source dust removal from industries through bag-house filter (BF), electrostatic precipitator (ESP) and wet scrubber (WS), and (f) area-source SO_2 removal from industries through limestone-gypsum flue gas desulphurization, wet flue gas desulphurization scrubber, spray dryer flue gas desulphurization, and phosphate ammonium fertilizer desulphurization process (PAFP). The economic objective of the air quality management strategy was to minimize the total emission control system cost while the environmental objective can still be satisfied. The environmental objective was reflected by the emission reduction objective of TSP, PM_{10} and SO_2 corresponding to an air-quality-guideline satisfaction percentage of 80% during the heating season. Thus the optimization model comprehensively took into account the information of emission reduction objectives, emission abatement alternatives, emission reduction cost, and related resources constraints. Consequently an optimal emission abatement strategy and the related cost were obtained for various pollution control measures. The results would provide sound bases for decision makers in terms of effective urban air quality management in the study city, and the proposed method is also applicable to many other cities for addressing their adverse air pollution problems in a cost-effective manner.

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