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APPLICATIONS OF INFORMATICS IN ENVIRONMENT ENGINEERING AND MEDICINE

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CHAPTER 1

Water and Air Quality Management

APPLICATION OF CONTINUOUS OPTIMIZATION METHODS TO EMISSION ABATEMENT PROBLEM

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The paper addresses problems of application of the air pollution forecasting models for supporting decisions concerning environment protection on a regional scale. The controlled object considered encompasses a set of point-wise emission sources, with a known location and emission characteristics. A set of emission reduction technologies with known efficiency and the unit cost is available. The goal is to assign a specific technology to each source, to reach the assumed environmental standard, subject to some economic constraints. The problem is formally stated as integer type, constrained minimization of certain objective function. In this paper an alternative, continuous formulation of the original problem is presented, where the differentiability of the cost functional and constrains can be utilized. Gradient optimization methods have been implemented and tested on the real data for the selected region. The case study relates to the set of major power plants in Silesia Region (Poland) and the basic desulphurization technologies, which are to be allocated.

Keywords: Air pollution, emission abatement, optimization methods.

1. Introduction

The paper deals with the problem of regional strategy of environmental quality protection and computer methods, which enable us to build the respective decision support tools. The main problem relates to the regional-scale strategy for air quality control, mainly due to sulfur oxide pollution. The objective is to formulate computer procedure of a complex analysis of cost-effectiveness and environmental impact related to specific emission abatement technologies.

The problem of sulfur and nitrogen oxide emissions is particularly severe in Central-East Europe, where high concentrations and depositions have already led to serious ecological damage. One of the most polluted areas in this region is Poland. Air quality deterioration is mainly due to sulfur and nitrogen oxides, emitted by a number of power and heating plants, heavy industry and domestic sources. The most significant environmental damage is caused by the energy sector, since the dominating source of electric power generation still is coal (hard coal and lignite) combustion. The modernization of this sector and emission reduction is one of the fundamental problems considered nowadays (Ciechanowicz et al. 1996).

At present there is a strong pressure to implement the formal instruments for reduction of air pollution emissions. The strategy of regional-scale emission abatement depends on the criteria upon which the environmental damage is evaluated. The straightforward approach is based on the emission reduction in all the plants by the fixed percentage or proportionally to the current emission intensity. This approach, however, is not the most efficient from environmental and economic point of view. Other strategies can also be formulated, where the main criterion of the optimality is the final environmental effect.

The direct application of environmental models is forecasting of dispersion of pollutants. On the other hand, many important decisions in air pollution and environmental problems, which could be supported by the respective models, are directly made by decision makers. The specialized decision support systems based on environmental forecasting models can be utilized in this area. Moreover, integration of optimization methods with environmental models gives the possibility of implementation of air pollution control strategies. Some examples of such applications can be found in the quoted bibliographical items.

One of the possible methods to improve air quality and to reduce environmental impact of energy sector is to apply desulphurization technologies in major plants. The unit cost and the efficiency of emission reduction can be taken into account, and the problem can be formulated in term of the optimization technique. One can consider some formal procedures, which support decisions concerning optimal (in some sense) selection of desulphurization technologies for the set of power or heating plants. The problem was stated and discussed in the previous papers (Holnicki, Kałuszko, 2004), where also some computational methods were presented. Since the respective optimization problem is of integer type -- the specialized, heuristic integer algorithm was applied.

In this paper another approach is presented, and continuous algorithm is applied for solving the original, discrete problem. As will be shown in the next sections, under some additional assumptions, the continuous optimization algorithm can generate the solution of integer type. Moreover, the method is more flexible and accurate than the previous integer algorithms. The main idea of the approach is presented in Section 3, while Section 4 presents results of the real data test and comparison of the both methods, regarding performance, flexibility and accuracy.

2. Air pollution dispersion model

Pollution transport model is one of the basic components of any complex decision support system, aimed at analysis of air quality. Depending on the time horizon of this analysis, the respective type of the forecasting model should be applied. In case of a long-term air quality strategy – the relevant, annual or seasonal forecast of pollution dispersion should be generated by the forecasting model. In our case, the year-averaged forecast of a dynamic transport model is utilized. Such a forecast reflects characteristics of emission field, but also the spatial and temporal evolution of the wind field in the forecasting period.

Dynamic air pollution transport models can also be used as a base for constructing the real-time emission control systems. In such a case, the optimal control problem is formulated as on-line minimization of an environmental cost function, by the respective modification of emission level in a set of the controlled sources, according to the changing meteorological conditions. This problem was discussed in (Holnicki, Kałuszko, 2003; 2004).

It is assumed in the sequel that the pollution transport process can be considered as distributed parameter system, governed by the transport equation. Implementation discussed here is sulfur-oriented, but the approach can be extended on a more general class of the forecasting models.

Computation of the transport of sulfur pollution is carried out by the Lagrangian type, three-layer trajectory model (Holnicki, et al. 1994; 2000). The mass balance for the pollutants is calculated for air parcels following the wind trajectories. The model takes into account two basic polluting components: primary – SO_2 and secondary – $SO_4^{=}$. Transport equations include chemical transformations $SO_2 \rightarrow SO_4^{=}$, dry deposition and the scavenging by precipitation. The main output constitutes the concentrations of SO_2, averaged over the discretization element and the vertical layer height. The governing equation, considered in one vertical layer, has the following, general form

$$\frac{\partial c}{\partial t} + \vec{\upsilon}\nabla c - K_h \,\Delta c + \gamma c = Q + \sum_{i=1}^{N} u_i \tag{1}$$

along with the respective boundary and initial conditions (Holnicki, et al. 2000).

Here Ω is the domain considered, T – time interval, c – pollution concentration, $\vec{\upsilon}$ – wind velocity vector, K_h – horizontal diffusion coefficient, γ – scavenging factor. The emission field on the right side of (1) is composed of the background (uncontrolled) emission field $Q(x, y, t)$ and the controlled part, which represents the impact of the controlled emission sources – $u_i = \chi_i(x, y)\, q_i(t)$.

Numerical algorithm is based on the discrete-time, finite element spatial approximation, combined with the method of characteristics (Holnicki, et al. 2000). The uniform space resolution step $h = \Delta x = \Delta y$ is applied in the computational algorithm. The mass balance for the pollutants is calculated for air parcels following the wind trajectories. Points along the trajectory are determined at discrete time points, based on the predefined interval – τ.

An important assumption made in the sequel is linearity of the process of pollution dispersion. If the linear dependence between emission of the source and the final concentration is assumed, the superposition principle can be applied in calculation of the total concentration map. Such an approach significantly simplifies any optimization procedure concerning emission control.

3. General statement of the optimization problem

This section presents an example of application of the forecasting model as a decision support tool for environmental quality protection. Our goal is to find a method for allocation of emission reduction technologies in a set of emission sources. The method is based on minimizing the environmental cost function subject to the constraint of the total cost of implementation of these technologies. A natural formulation of the problem has a form of integer programming, constrained minimization, stated in section 3.1. To solve such problem, some non-gradient, heuristic methods must be applied (Holnicki, Kałuszko, 2003). In section 3.2 an alternative, continuous formulation of the problem is presented, where the advantages of the gradient optimization methods can be utilized.

3.1 Discrete problem formulation

Assume that there are N controlled SO_2 emission sources located in a region Ω. Moreover, we have M available technologies for emission reduction. Each desulphurization technology is characterized by certain effectiveness and the unit cost (both for investment and operational costs). Basing on these data, certain optimization problems concerning environmental quality can be formulated. One of the possible questions can deal with the optimal allocation of desulphurization technologies to emission sources. The goal is to minimize certain environmental damage index (the objective function) subject to constraints on investment and operational costs, in given period T. Another class of problems can be related to obtaining certain threshold of environmental quality index under the minimal cost.

To formally state the optimization problem, the necessary notation must be introduced. We shall denote in the sequel: $\Omega = L_x \times L_y$ – rectangle area under consideration, N – number of controlled sources, M – number of available desulphurization technologies, C_T – constraint on total, annual cost (investment and operational), $\vec{u} = [u_1, u_2, \ldots, u_N]$ – emission vector of controlled sources, $\vec{e} = [e_1, e_2, \ldots, e_M]$ – effectiveness vector of desulphurization technologies applied, $F = \{f_{ij}\}, (1 \le i \le N,\ 1 \le j \le M)$ – matrix of abatement cost per unit emission,

$X = \{x_{ij}\}, (1 \le i \le N,\ 1 \le j \le M)$ – "0-1" matrix of technology assignment to the controlled sources (decision variable matrix).

Definition of the environmental criterion, which is to be minimized, depends on the objectives of the control strategy which is considered. We define here a global environmental cost function of the following form:

$$J(c) = \frac{1}{2} \int_{\Omega} w(x, y) \max{}^2 (0, c(x, y) - c_{ad})\, d\Omega \tag{2}$$

where: $w(x, y)$ – area sensitivity (weight) function, c_{ad} – admissible level of SO_2 concentration.

The concentration forecast, considered as the solution to (1), is calculated as

$$c(x, y) = c_o(x, y) + \sum_{i=1}^{N} A_i(x, y) \cdot u_i, \qquad (x, y) \in \Omega \tag{3}$$

where $c_o(x, y)$ – background concentration (impact of uncontrolled sources), $A_i(x, y)$ – transfer matrix (relation emission → concentration) of the i-th source.

The unit transfer matrices $A_i(x, y)$, $(i = 1, \ldots, N)$ for the controlled sources are preprocessed off-line by the respective forecasting model (Holnicki, et al. 1994, 2000, 2001). In a similar way, the background pollution field, $c_o(x, y)$ is computed for uncontrolled, background emissions, including the inflow from the neighboring regions. The current emission intensity of the i-th source depends on the initial emission value – u_i^o and efficiency of the abatement technology applied, according to the formula

$$u_i(x, y) = u_i^o \sum_{j=1}^{M} (1 - e_j) \cdot x_{ij}, \quad \sum_{j=1}^{M} x_{ij} = 1, \quad x_{ij} \in \{0,1\}, \quad 1 \le i \le N, \tag{4}$$

where u_i , u_i^o denote the current and the initial emission intensity of the i-th source, respectively.

Cost of emission abatement in each source consists of two components: investment cost and operational cost. Both types of the costs depend on the specific abatement technology and on the parameters of the energy installation where this technology is to be applied. Here a simplified approach is utilized, where the investment cost of the j-th abatement technology installed in the i-th emission source is calculated as annual cost, averaged over the entire amortization period.

Thus, the total emission abatement cost per year, considered as a sum of desulphurization costs in the respective plants, is calculated in the following form:

$$C_T = \sum_{i=1}^{N} c_i = \sum_{i=1}^{N} u_i^o \sum_{j=1}^{M} f_{ij} x_{ij} = \sum_{i=1}^{N} u_i^o \sum_{j=1}^{M} (f_{ij}^1 + f_{ij}^2) x_{ij}, \tag{5}$$

where the coefficients: f_{ij}^1, f_{ij}^2, f_{ij} denote here the averaged annual, investment, operational and total cost, respectively, of the j-th technology applied to the i-th emission source.

Basing on the above notation, we can formulate optimization problem, aimed at selection of emission abatement technologies. Depending on the criterion function and the constraints – the following two complementary problems can be considered:

Discrete problem (DP) of optimal selection of emission abatement technologies

Determine the set of emission reduction technologies

$$X_{ad} = \{x_{ij} \in \{0,1\} : u_i = u_i^o \sum_{j=1}^{M} (1 - e_j) x_{ij}, \ \sum_{j=1}^{M} x_{ij} = 1, \ 1 \le i \le N, \ 1 \le j \le M\}, \tag{6}$$

in such a way that

(DP-A) – minimization of environmental cost

the environmental cost function (1) is minimized

$$J(c(X_{ad})) \Rightarrow \min \tag{7a}$$

subject to the total cost constraint

$$C_T = \sum_{i=1}^{N} c_i \le C_{MAX} \tag{7b}$$

(DP-B) – minimization of technological cost

the assumed environmental standard is obtained

$$J(c(X_{ad})) \le J_{MAX} \tag{8a}$$

at the minimal cost of the emission abatement technologies utilized

$$C_T = \sum_{i=1}^{N} c_i \Rightarrow \min . \tag{8b}$$

The original two problems formulated above are stated as integer programming type optimization. An heuristic algorithm of direct solving (DP-A) problem was presented in (Holnicki, Kałuszko, 2003), while in (Stańczak, et al. 2003) the solution was obtained by genetic algorithm. The next sections characterize a different approach, where the problem is considered as a continuous optimization.

3.2 Continuous formulation of the optimization problem

In some applications an alternative formulation of the problem as continuous one can be considered and implemented. In this approach, the modified formulations of the optimization problems stated in Section 3.1 are considered, where the decision variables are continuous functions $x_{ij} \in \langle 0,1 \rangle$. Such an approach admits technologically unrealistic, fuzzy form of the final solution, but enables us to utilize differentiability of the objective function and construct very efficient optimization algorithm. Some other advantages of this approach will be discussed below.

The continuous formulation of the optimization problem (5) – (8) requires the respective modification of the set of admissible solutions (6), which in this case has a following form

$$X_{ad} = \{x_{ij} \geq 0 : \sum_{j=1}^{M} x_{ij} = 1, \quad 1 \leq i \leq N, \quad 1 \leq j \leq M\}.$$

Formulations of the objective functions and the constraints remain unchanged. Thus, we can consider two continuous versions of the optimization problem: (6), (7), (8).

Continuous problem (CP) of the optimal selection of emission abatement technologies

Determine the set of emission reduction technologies as the solution of

(CP-A) – minimization of environmental cost according to conditions (7a-b),

(CP-B) – minimization of technological cost according to conditions (8a-b,)

for the set of admissible solutions

$$X_{ad} = \{x_{ij} \geq 0 : u_i = u_i^o \sum_{j=1}^{M} (1-e_j) x_{ij}, \ \sum_{j=1}^{M} x_{ij} = 1, \ 1 \leq i \leq N, \ 1 \leq j \leq M\}. \tag{9}$$

In this case, however, we can formally calculate gradient of the objective function and utilize it in the optimization algorithm. Depending on the specific optimization problem, components of the gradient have a form:

Problem A:

$$\frac{\partial J}{\partial x_{ij}} = u_i^o\,(1-e_j)\int_\Omega w(x,y)\,\max[0, d(x,y) - d_{ad}]\,A_i(x,y)\,d\Omega \qquad (10)$$

$$(i=1,\ldots,N;\; j=1,\ldots,M).$$

Problem B:

$$\frac{\partial C_T}{\partial x_{ij}} = u_i^o f_{ij} = u_i^o (f_{ij}^1 + f_{ij}^2), \quad (i=1,\ldots,N;\; j=1,\ldots,M). \qquad (11)$$

Definition of the continuous problem (CP) admits combination of some desulphurization technologies in the optimal solution. Such a fuzzy form of the solution is technologically unrealistic, but it gives very precise approximation of the real, integer-type optimal solution. For this reason it can be used as the reference data, for evaluation accuracy of some dedicated, heuristic algorithms. Moreover, the fuzzy-form solution can also be utilized, in the most of the practical situations, in a direct supporting decisions concerning emission abatement.

It is shown below that by introducing certain minor modifications in the set of admissible solutions (9) of the continuous problem (CP) we get "almost integer" form of the optimal solution. On the other hand, the advantages of the continuous formulation (gradient optimization algorithm, performance and accuracy) remain valid. This form of the continuous optimization is stated below as the modified continuous problem (MP).

The stated below problem is modification of continuous formulation (CP). The modification is related to the set of admissible solutions, X_{ad}.

Modified problem (MP) of the optimal selection of emission abatement technologies

Determine the set of emission reduction technologies as the solution of

(MP-A) – minimization of environmental cost according to conditions (7a-b),

(MP-B) – minimization of technological cost according to conditions (8a-b,)

for the set of admissible solutions

$$X_{ad} = \{x_{ij} \geq 0:\; u_i = u_i^o \sum_{j=1}^{M} (1-e_j)\,x_{ij}^2,\; \sum_{j=1}^{M} x_{ij}^2 = 1,\; 1 \leq i \leq N,\; 1 \leq j \leq M\}. \qquad (12)$$

In this case we can also formally calculate gradient of the objective function. It follows from the objective function (2) that the final form of the gradients of the objective functions in the modified continuous problems (MP) can be expressed in the following form:

Problem A:

$$\frac{\partial J}{\partial x_{ij}} = 2u_i^o\,(1-e_j)\cdot x_{ij}\int_{\Omega} w(x,y)\ \max[\,0, d(x,y) - d_{ad}\,]\ A_i(x,y)\,d\Omega$$

$$(i=1,\dots,N;\ j=1,\dots,M) \qquad (13)$$

Problem B:

$$\frac{\partial C_T}{\partial x_{ij}} = 2u_i^o f_{ij}\cdot x_{ij} = 2u^o(f_{ij}^1 + f_{ij}^2)\cdot x_{ij}, \quad (i=1,\dots,N;\ j=1,\dots,M) \qquad (14)$$

General approaches formulated above have been tested on the real-data case study. Results of the test computations and comparison of the discrete and continuous formulations are presented in the next section.

4. Case study analysis

4.1 Computational domain and emission sources

The optimization methods discussed in Section 3 were applied in the real-data case for selection of desulphurization technologies in the major power plants located in the industrial region of Upper Silesia (Poland). The region is characterized by high concentration of heavy industry and the energy sector installations.

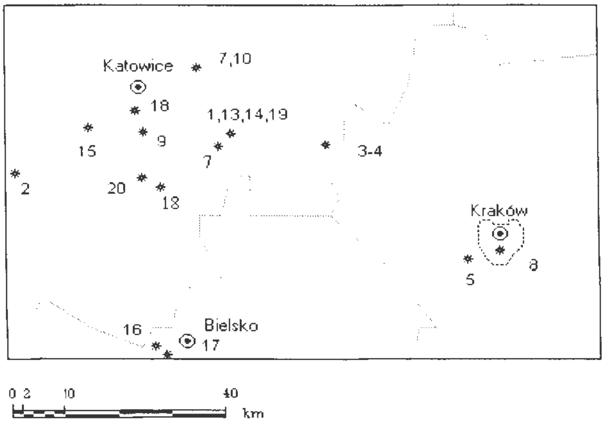

Figure 1. Computational domain and location of the emission sources

The domain considered is a rectangle area 110 km x 76 km. In this area 20 major power plants were selected and considered as the controlled sources. Moreover, certain number of medium and small industrial sources constitutes a background emission field. The domain is discretized, for the computational purposes, with the homogeneous grid, (the step size $h = 2$ km). The location of the controlled emission sources is shown in Fig. 1.

Table 1. Characteristics of the controlled emission sources

	Source	Coord.	h [m]	Emiss . [t/d]	Unit abatement cost [US$ / gSO_2]				
					Abatement technologies				
1	Jaworzno III	(21,24)	250	303.2	.00	.10	.09	.38	.43
2	Rybnik	(1,20)	200	225.2	.00	.18	.17	.63	.74
3	Siersza A	(30,23)	150	104.0	.00	.04	.09	.37	.44
4	SierszaB	(30.23)	260	91.8	.00	.05	.10	.42	.51
5	Skawina	(43,11)	120	90.1	.00	.10	.18	.74	1.1
6	Łaziska I	(8,20)	200	78.0	.00	.12	.19	.77	.87
7	Będzin B	(18,31)	200	65.0	.00	.13	.18	.72	.86
8	Łęg	(46,12)	250	52.0	.00	.35	.29	.25	1.5
9	Katowice	(13,25)	250	52.0	.00	.10	.16	.64	.75
10	Będzin A	(18,31)	160	45.1	.00	.14	.20	.78	.93
11	Łaziska II	(8,20)	160	34.7	.00	.13	.22	.86	.98
12	Łaziska III	(8,20)	100	33.8	.00	.06	.10	.41	.47
13	Jaworzno IIA	(21,24)	120	29.9	.00	.17	.20	.80	1.0
14	Jaworzno IIB	(21,24)	100	25.1	.00	.15	.17	.71	.93
15	Halemba	(8,25)	110	26.0	.00	.11	.22	.93	1.2
16	Bielsko-Biała	(14,2)	140	18.7	.00	.11	.24	1.0	1.3
17	Bielsko-	(15,1)	250	16.9	.00	.16	.36	1.5	1.9
18	Chorzów	(12,27)	100	15.1	.00	.18	.40	1.6	2.1
19	Jaworzno I	(20,23)	152	12.3	.00	.31	.36	1.5	1.9
20	Tychy	(13,19)	120	11.6	.00	.27	.60	2.4	3.1

In the example discussed in the sequel, 8 desulphurization technologies are taken into account (5 basic technologies and 3 combined). The technologies and the respective emission reduction efficiencies are as follows:

- "do nothing" technology ($e = 0$),
- low-sulfur fuel ($e \cong 0.30$),
- dry desulphurization method ($e \cong 0.35$),
- low-sulfur fuel + dry desulphurization method ($e \cong 0.545$),

- half-dry desulphurization method ($e \cong 0.75$),
- low-sulfur fuel + half-dry desulphurization method ($e \cong 0.825$),
- MOWAP method ($e \cong 0.85$),
- low-sulfur fuel + MOWAP method ($e \cong 0.895$).

The emission source is characterized by the nominal emission intensity and the unit cost of abatement technology installation, which is composed of investment and operational cost. In this paper we consider one, aggregated unit abatement cost, assigned to the specific source and depending on the technology. The location of the sources, emission characteristics and the unit abatement costs are shown in Table 1.

The annual unit concentration maps for the controlled sources -- the transfer matrices ($A_i(x, y)$, $i = 1, \cdots, N$) -- are preprocessed off-line by the regional-scale forecasting model, mentioned in the previous section. The same technique is used for generating the background concentration field for the minor point-wise and area sources. Computations were performed for one representative year, where a sequence of meteorological data with 12-hr time resolution was applied.

The next paragraph presents the selected results of test computations, performed by the modified continuous optimization algorithms (MP-A) and (MP-B). An attention is focused on the accuracy and elasticity of this approach, especially in comparison with the direct, integer-type (DP) and continuous (CP) algorithms.

4.2 Results obtained by the modified continuous method

The first set of the computation relates to the comparison of solutions of the continuous optimization problem (CP-A) and the modified (MP-A) problem. Computations were repeated for several levels of the total cost constraint. Table 2 shows an example of the continuous solution to the problem (CP-A) get for the total cost constraint 150 mil. US$/yr. Columns of the above tables refer to 8 abatement technologies, according to their increasing efficiency. The last column of the table shows the list of the reduced emissions, related to the optimal solution.

The solution of the basic, continuous problem (CP-A) presented in Table 2 has an unrealistic, distributed form, where abatement technology assigned to one source is a weighted sum of several technologies. The related solution to (MP-A) problem is shown in Table 4 and is significantly better (less fuzzy) than those obtained directly by the continuous method (CP-A). In spite of the continuous character of the algorithm and the control variables – the solution is of integer type for most of the emission sources.

Results presented in Tables 3 – 5 (obtained for 3 levels of cost constraint) illustrate the basic advantages of the modified (MP) approach in comparison with the direct discrete solution (DP) obtained by heuristic or evolutionary algorithms.

Table 2. Solutions of (CP-A) problem for the cost constraint 150 mil.$/yr.

Src. No	initial emiss.	abatement technology								Final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	**0.01**	**0.99**	0.00	0.00	0.00	0.00	137.99
2	225.30	**0.58**	**0.36**	**0.05**	0.00	0.00	0.00	0.00	0.00	195.30
3	104.00	0.00	0.00	**0.01**	**0.99**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	0.00	**0.01**	**0.22**	**0.27**	**0.50**	9.64
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	**0.26**	**0.72**	**0.02**	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	**0.10**	**0.84**	**0.05**	**0.01**	0.00	0.00	0.00	0.00	4550
8	52.00	**0.39**	**0.49**	**0.11**	**0.01**	0.00	0.00	0.00	0.00	39.55
9	52.00	**0.99**	0.00	**0.01**	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	**0.00**	**0.33**	**0.13**	**0.54**	0.00	0.00	0.00	0.00	20.52
11	34.70	**0.30**	**0.48**	**0.17**	**0.05**	0.00	0.00	0.00	0.00	24.29
12	33.80	0.00	0.00	0.00	**0.01**	**0.01**	**0.05**	**0.63**	**0.31**	5.07
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	**0.06**	**0.94**	3.14
14	25.10	0.00	0.00	0.00	**0.02**	**0.01**	**0.41**	**0.14**	**0.42**	3.39
15	26.00	0.00	0.00	0.00	**0.07**	**0.30**	**0.33**	**0.25**	**0.05**	4.63
16	18.70	0.00	**0.03**	**0.07**	**0.66**	**0.13**	**0.06**	**0.03**	**0.01**	8.51
17	16.90	**0.24**	**0.51**	**0.13**	**0.11**	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	**0.29**	**0.06**	**0.29**	**0.15**	**0.20**	2.92
19	12.30	**0.07**	**0.59**	**0.11**	**0.23**	0.00	0.00	0.00	0.00	8.61
20	11.60	0.00	0.00	0.00	0.00	**0.02**	**0.10**	**0.20**	**0.68**	1.22

The calculations were performed for three levels of the total cost constraints: 100, 150 and 200 mil. US$/yr., respectively. The optimal solution, in this case, means the minimum of the objective function (2). It is obvious that the higher financial limit is admitted, the more effective technologies are selected and the emissions of the respective sources are accordingly reduced. Emission reduction in a specific source is not proportional to the initial intensity, because the selection of the abatement technology depends not only on the emission intensity itself, but also on the unit cost of the technology applied to this source.

Results of (MP-A) algorithm are directly compared with the respective integer-type solutions, obtained by the evolutionary method. The strict correspondence between two types of solutions can be observed. Reduction of the initial value of the environmental cost index (the objective function) does not depend on the optimization algorithm applied, and is 0.19, 0.113, 0.069, respectively for three levels of the cost constraint: 100, 150 and 200 mil. US$/yr.

It can be also immediately noticed that the character of (MP-A) solution is almost of integer type, and is significantly better than those obtained by the original continuous algorithm (CP-A). Only about 15 – 20% of the selected solutions is a combination of two basic abatement technologies. On the other hand, the optimum is reached for the lower value of the quality function, than those of discrete solution,

Table 3. Solution to (MP-A) – top and (DP) – bottom. Cost constraint 100 mil $/yr.

No	initial emiss.	abatement technology								final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	197.08
2	225.30	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	225.30
3	104.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	**0.63**	0.00	**0.30**	0.00	**0.07**	31.88
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	**0.68**	**0.32**	0.00	0.00	0.00	0.00	0.00	0.00	70,39
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	31.56
11	34.70	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34.70
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	5.07
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.13
14	25.10	0.00	0.00	0.00	**0.37**	0.00	**0.63**	0.00	0.00	7.00
15	26.00	0.00	0.00	0.00	**0.60**	**040**	0.00	0.00	0.00	9.64
16	18.70	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	8.50
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	6.87
19	12.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	8.61
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.22

No	initial emiss.	abatement technology								final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	197.08
2	225.30	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	225.30
3	104.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	41.77
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	31.56
11	34.70	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34.70
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	5.07
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.14
14	25.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	11.42
15	26.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	6.50
16	18.70	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	8.51
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	6.87
19	12.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	8.61
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.21

Table 4. Solution to (MP-A) – top and (DP) – bottom. Cost constraint 150 mil $/yr.

No	initial emiss.	abatement technology								final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	137.95
2	225.30	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	225.30
3	104.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.64
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	**0.20**	**0.80**	0.00	0.00	0.00	0.00	0.00	0.00	39.46
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	20.52
11	34.70	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	24.29
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	5.07
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.14
14	25.10	0.00	0.00	0.00	0.00	0.00	**0.45**	0.00	**0.55**	3.40
15	26.00	0.00	0.00	0.00	**0.03**	**0.97**	0.00	0.00	0.00	6.52
16	18.70	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	8.51
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	**0.06**	0.00	**0.94**	0.00	0.00	2.92
19	12.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	8.61
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.22

N	initial emiss.	abatement technology								final emiss.
		1	2	3	4	5	6	7	8	
1	303.2	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	137.9
2	225.3	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	225.3
3	104.0	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.64
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	36.40
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	20.52
11	34.70	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	24.29
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	5.07
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.14
14	25.10	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	4.39
15	26.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	6.50
16	18.70	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	8.51
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	2.64
19	12.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	8.61
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.22

Table 5. Solution to (MP-A) – top and (DP) – bottom. Cost constraint 200 mil $/yr.

No	initial emiss.	abatement technology								final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	0.00	**0.28**	0.00	0.00	**0.72**	0.00	71.57
2	225.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	157.71
3	104.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.64
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	36.40
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	20.52
11	34.70	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	24.29
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.55
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.14
14	25.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	2.64
15	26.00	0.00	0.00	0.00	0.00	0.00	**0.01**	**0.99**	0.00	3.91
16	18.70	0.00	0.00	0.00	**0.01**	**0.91**	**0.08**	0.00	0.00	4.62
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.60
19	12.30	0.00	**0.12**	0.00	**0.88**	0.00	0.00	0.00	0.00	5.84
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.22

No	initial emiss.	abatement technology								final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	75.75
2	225.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	157.71
3	104.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.64
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	36.40
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	20.52
11	34.70	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	22.56
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.55
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.14
14	25.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	2.64
15	26.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	0.00	3.91
16	18.70	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	8.51
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.60
19	12.30	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	5.60
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.22

Table 6. Solution to (MP-B) problem for environmental cost reduction – 0.069

No	initial emiss.	abatement technology								Final emiss.
		1	2	3	4	5	6	7	8	
1	303.20	0.00	0.00	0.00	**0.28**	0.00	0.00	**0.72**	0.00	71.51
2	225.30	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	157.71
3	104.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	47.32
4	91.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.64
5	90.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	9.46
6	78.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	54.60
7	65.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	45.50
8	52.00	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	36.40
9	52.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.00
10	45.10	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00	0.00	20.52
11	34.70	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	24.29
12	33.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.55
13	29.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	3.14
14	25.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	2.64
15	26.00	0.00	0.00	0.00	0.00	0.00	**0.01**	**0.99**	0.00	3.91
16	18.70	0.00	0.00	0.00	**0.01**	**0.91**	**0.08**	0.00	0.00	4.62
17	16.90	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	11.83
18	15.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.60
19	12.30	0.00	**0.12**	0.00	**0.88**	0.00	0.00	0.00	0.00	5.84
20	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00**	1.22

obtained by the evolutionary method. Another important advantage of (MP) approach is the computing time, which is reduced 10 times approximately, comparing with those of the evolutionary method.

The graphical illustration of the optimal results discussed above is presented in Figures 2–3. They show four maps of SO_2 concentration: the initial state and the respective, modified pollution fields, related to selected emission abatement strategy represented by the optimal solutions shown in Tables 3 – 5.

The continuous algorithm can be easily formulated in the complementary form: *meet a given air quality standard subject the total cost constraint.* The respective optimization tasks have been stated in the previous paragraph as the discrete (DP-B), continuous – (CP-B) and the modified – (MP-B) algorithms. The criterion function to be minimized is the total cost (8b), while the constraint is the required reduction of the environmental index (8a). The assumed factor of environmental index reduction in the last test is set to 0.069. This allows us to directly compare results of two problems – presented in Table 4 solution of (MP-A) and that of Table 6, where the solution of (MP-B) task is shown. As one can see, in two cases considered the computational algorithm converges with high accuracy to the same optimum point (reduction of environmental index -- 0.069 and the total abatement cost --200 mil $/yr.).

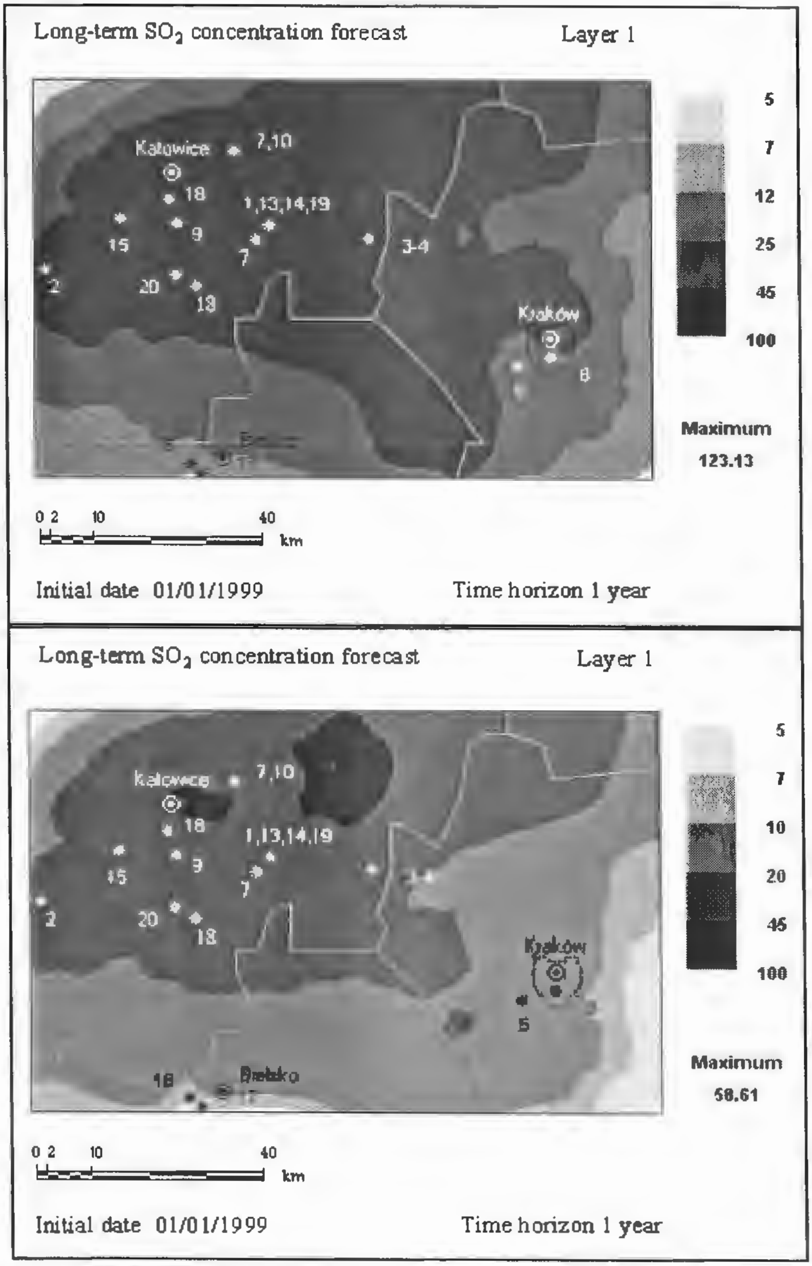

Figure 2. SO_2 concentration map initial (top) and for the cost constraint 100 mln \$/yr. (bottom)

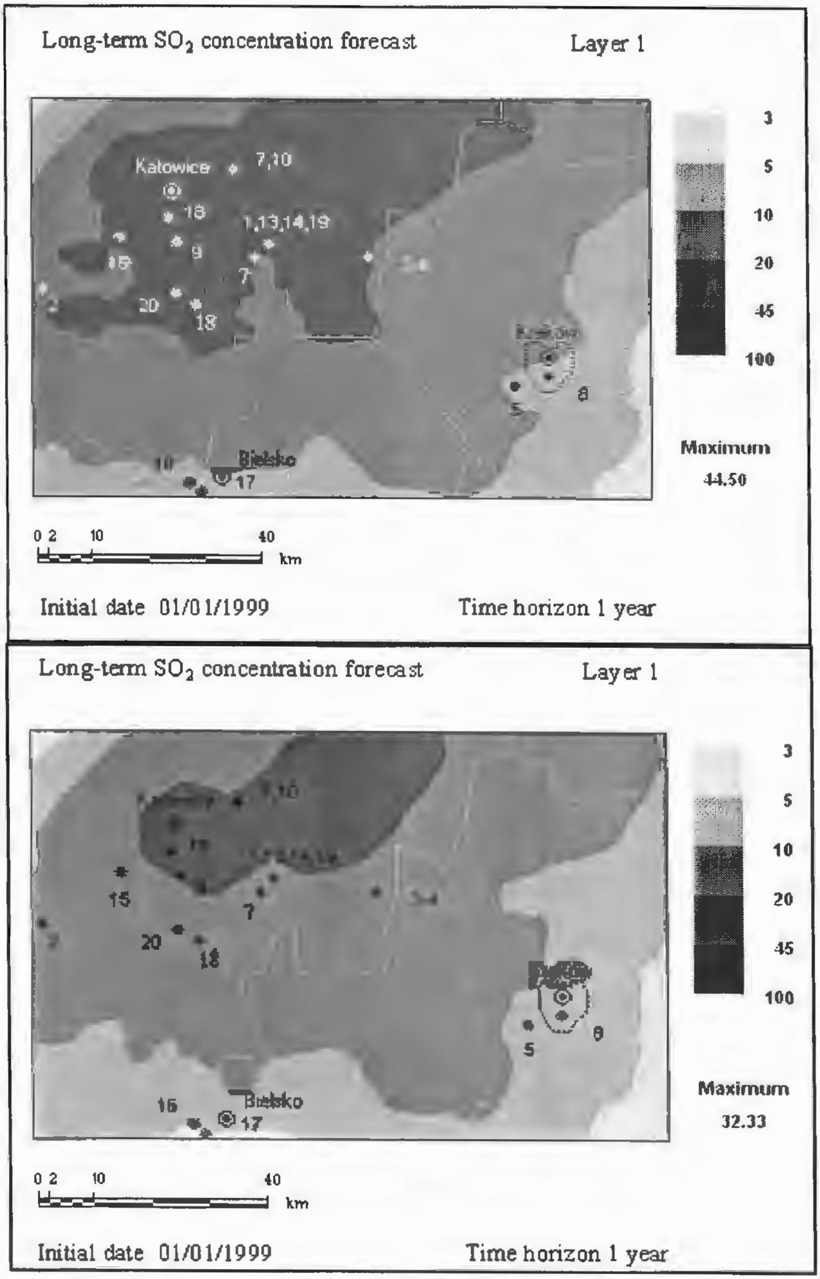

Figure 3. SO_2 concentration map for abatement cost constraint 150 mln \$/yr. (top), for abatement cost constraint 200 mln \$/yr. (botom)

5. Concluding remarks

The paper deals with the problem of the optimal selection of emission abatement technologies within a given set of power plants. The approach discussed in the paper is a modification of the heuristic method, designed for a direct solving of integer-type optimization problems, and considered in (Holnicki, Kałuszko, 2003; 2004). The main goal was to formulate and test the modified, continuous algorithm (MP), as a tool for solving the respective integer optimization problem. The basic feature of the method is that the natural, discrete problem is transformed for numerical purposes, to the respective continuous task.

Computational results presented in the previous section show that the considered here (MP) method allows us effectively solve a class of integer-type problems formulated in Section 3. General form of the solutions obtained is "almost" integer, which is absolutely satisfactory for any practical applications. On the other hand, the comparison with the other methods (Holnicki, Kałuszko, 2004; Stańczak, et al. 2005) shows good accuracy of the above results.

An important aspect of the algorithm, which should be pointed out, is the performance. Results obtained by (MP) algorithms were compared with the specialized heuristic method (Holnicki, Kałuszko, 2003) as well as with genetic algorithm approach (Stańczak, et al. 2005). Computing time of the method considered is comparable with the heuristic algorithm, but it gives much more flexibility in formulation of the optimization problem, which is to be solved (e.g. formulation of (MP-A) and (MP-B) problems). Genetic algorithm can generate a strict integer-type solution, but its computing time is about ten times longer than those of (MP) method.

The computational experiments confirm very good properties of (MP) algorithm from the viewpoint of performance and accuracy. It can be useful in analysis of the differentiable (as to criterion and constraints) optimization problems. Due to short computing time, it can be also applied in the real-time emission control. In case of the non-differential optimization, application of genetic algorithms (Stańczak, et al. 2005 can be considered.

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(Editors)

APPLICATIONS OF INFORMATICS IN ENVIRONMENT ENGINEERING AND MEDICINE

The purpose of the present publication is to popularize applications of informatics in environment and health engineering and protection. Runned papers are thematically chosen from the works presented during the conference *Multiaccessible Computer Systems* (*Komputerowe Systemy Wielodostępne*) that has been organized by the Systems Research Institute and University of Technology and Agriculture of Bydgoszcz for several years in Ciechocinek. Problems described in the papers concern quality management of the surface waters and the atmosphere, application of the mathematical modelling in environmental engineering, and development of computer systems in health and environmental protection. In several papers results of the research projects financed by the Polish Ministry of Science and Information Society Technologies are presented.

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