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tables,
diagrams

IPAC:

Industrial Planning Air Control System

User's Guide

Version 1.0
for IBM PC and Compatibles

18247

Prepared for the
United Nations Industrial Development Organization
Department of Industrial Operations

February 1990

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IPAC: Industrial Planning Air Control System

User's Guide

IPAC, version 1.0, was developed in 1990 for the Department of Industrial Operations, Industrial Planning Branch, of the United Nations Industrial Development Organization (UNIDO). Comments and inquiries should be addressed either to UNIDO, or directly to the authors: Dr. Vladimir Litwin, Laboratory for Natural Environment and Climate Monitoring of the State Committee for Hydrometeorology of the USSR Academy of Sciences, Glebovskaya str. 20b, Moscow 107258, USSR (Telephone: 4579607); or Dr. Sergei Golovanov, IIASA, A-2361 Laxenburg, Austria (Telephone: (02236)71521*0, Telefax: (02236)71313, E-mail: ...!tuvie!iiasa!sergei).

Introduction

The IPAC System is designed to provide valuable decision support for the problems of atmospheric protection and air quality management in industrial planning at the national, sectoral and enterprise levels. It can be used in areas up to 400 × 400 km (about 300 × 300 miles). The system can be applied to a variety of industrial areas, cities and relatively small states.

System Information

The software is divided into two main systems:

- a system designed for the IPAC "City" – urban areas up to 40 × 40 km (approximately 30 × 30 miles),
- a system designed for the IPAC "Region" – larger areas, up to 400 × 400 km, with different landscape features.

Both subsystems should be installed, stored in separate subdirectories.

Hardware Requirements

The following hardware is required to run IPAC:

- an IBM PC/AT, PC/386 or PS/2 running DOS 2.*nn* or greater, at least 512 KB RAM, an 80-87 coprocessor, a hard disk, and either an EGA or a VGA graphics adapter. The system currently supports the EPSON FX type dot matrix printers or good compatibles. Support for other types of printer will be provided in the later versions.
- a PC/XT could generally handle the software as well; however, on account of the sophisticated mathematical models incorporated in the the IPAC system, it is preferable to use a PC/386 with a coprocessor and RAM cache or RAM virtual drives to speed up model runs.

Installation

The entire distributed system is contained on one 5.25" high density diskette in compressed mode. To install the system:

1. Check that at least 3 MB of space is available on the hard disk where IPAC is to be installed. If only one of the two subsystems ("City" or "Region") is to be installed, 2 MB of free space is sufficient.

2. Insert the IPAC system disk into drive A and type:

   ```
   a:install (d:) ↵
   ```

   where d is the the name of the hard disk drive where the system is to be installed.

3. When the installation is complete, answer the appropriate questions.

4. Enter

   ```
   city ↵
   ```

   to run the "City" version of IPAC, or

   ```
   reg ↵
   ```

   to run the "Region" version of the IPAC system.

Working with the System

IPAC is a menu-driven system. Each menu consists of a choice of commands in the upper section, and a comment line in the lower section. The comments correspond to the command in the menu currently being highlighted. The comment line remains visible throughout each session with the system. Fig. 1 depicts the main menu of the IPAC system.

Data Preparation

The information required during the data preparation phase of the IPAC system is divided into 5 parts, as presented in Fig. 2. A more detailed description is presented in the *IPAC System Handbook*. Similar forms of data entry are used during each stage of data preparation. The comments on the bottom line describe the control key functions and identify appropriate actions. It is important to enter suitable data before starting system simulations. Inproper data input can lead to unpredictable results.

During data entry, the system checks the validity of all data entered. The absolute values of all integers are checked against a predefined interval; all real numbers are checked by the number decimal places to the left and right of the decimal point. It may happen during data entry that the user is unable to leave the data entry cell where he just entered data. This means that the number entered is outside of the range allowed by the system and it must be replaced by one that is in-range.

Two types of form are used for data entry: singular and multiple. In the singular data entry form, only one set of data can be seen or input. In the multiple data entry form, each form represents only one set of data within the database; the whole database consists of many data sets.

Singular data forms are Geography, Meteorology, Chemistry, and the Measures Group. Multiple data forms are Emission Sources, Measures, Sigma, and Pairs. A detailed description of each of the forms follows.

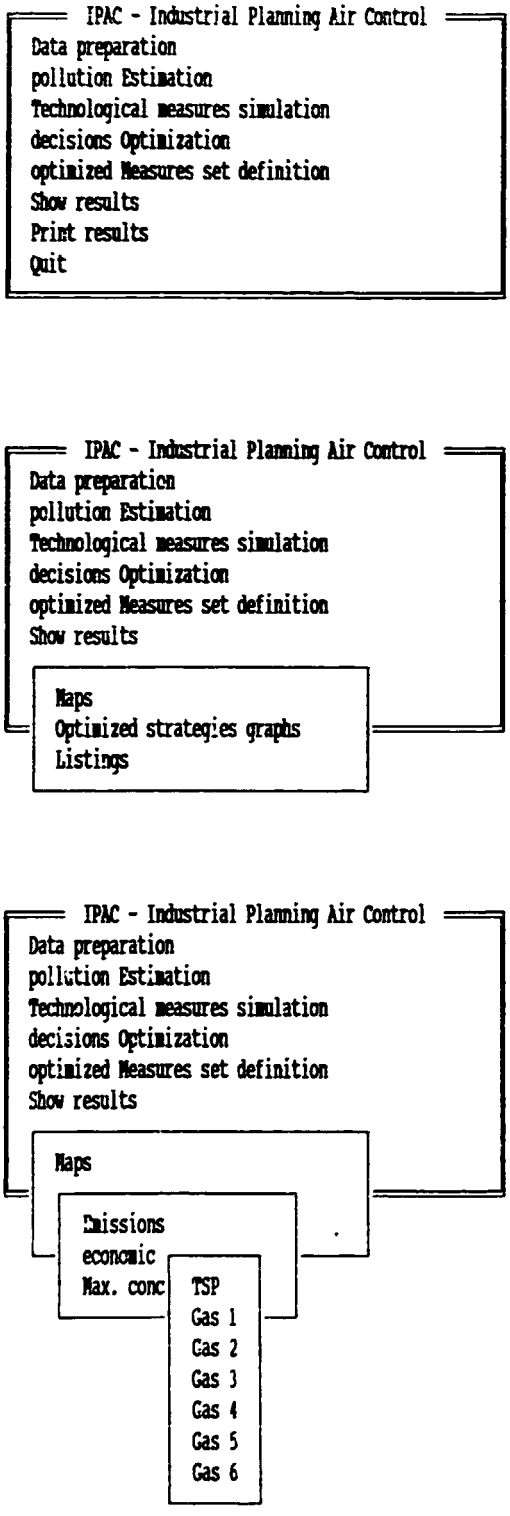

Fig. 1: Main menu.

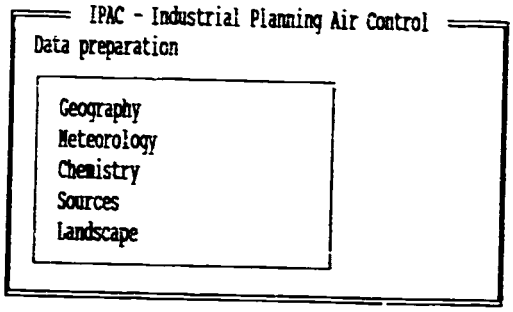

Fig. 2: Data preparation menu.

Enter geographical data about the region one dataset must exist

Region Name	Dirty Smokes Valley
Number of cells for West-East direction (X-axes)	12
Number of cells for South-North direction (Y-axes)	9
Grid step (km)	10.0
Average population density (per sq.Km)	900.0

Fig. 3: Data entry form "Geography".

Geographical data

The data entry form "Geography" is depicted in Fig. 3. This form requires a minimal set of geographical data about the city/region to be entered into the system.

Meteorological data

The "Meteorological" data entry forms for the city and the region are presented separately in Fig. 4 and Fig. 5, respectively, The region forms contain data not included in the city forms on: average wind reiteration for the boundary layer, height of boundary layer, wind speed distribution (atmospheric stratification parameter), and precipitation.

Chemistry data

Chemistry data consists of the names and aggressiveness coefficients of pollutants for which calculations will be made. In the city forms, values of maximum occasional permissible concentrations (MOPC) are also included. Sample "Chemistry" data entry forms for the city and the region are presented in Fig. 6 and Fig. 7, respectively.

Enter meterological data about the city: one dataset must exist

Mean annual surface air temperature (C) 5.0

Average surface air temperature in July or January (C) 19.0

Mean annual surface wind speeds (m/s) 5.5

Wind reiteration from South 0.150 from North 0.100

Wind reiteration from S-West 0.170 from N-East 0.100

Wind reiteration from West 0.130 from East 0.110

Wind reiteration from N-West 0.100 from S-East 0.140

Edit | ↓-Next ↑-Prev F2-Accept Esc-Cancel

Fig. 4: Data entry form "Meteorology" for the city.

Enter meterological data and wind reiterations one dataset must exist

Surface air temper. (C) 5.0 Precipitation (mm) 600

Surface wind speed (m/s) 5.1 Wet period duration 0.12

Wind from South 0.400 S-West 0.100 West 0.100 N-West 0.050

Wind from North 0.050 N-East 0.050 East 0.050 S-East 0.200

Mean annual boundary layer height (m) 750

Direction 1 0.2000 Dir.2 0.2000 Dir.3 0.0500 Dir.4 0.0500

Direction 5 0.0500 Dir.6 0.0500 Dir.7 0.0500 Dir.8 0.0500

Direction 9 0.0500 Dir.10 0.0500 Dir.11 0.1000 Dir.12 0.1000

View | Enter-edit Esc-Exit

Fig. 5: Data entry form "Meteorology" for the region.

Enter pollutants data: one dataset must exist

	Pollutant Name	Agressiveness	MOPS
TSP	Cement Dust	45.0	0.500000
Gas1	SO2	16.5	0.500000
Gas2	NOx	41.1	0.085000
Gas3	NH3	4.6	0.200000
Gas4	HF	980.0	0.020000
Gas5	CO	1.0	5.000000
Gas6		0.0	0.000000

Edit | ↓-Next ↑-Prev F2-Accept Esc-Cancel

Fig. 6: Data entry form "Chemistry" for the city.

Enter pollutant data: one dataset must exist

	Pollutant Name	Agressiveness
TSP	Cement Dust	45.0
SO2	Sulfur Dioxide	22.0
NOx	Nitrogen Oxides	41.1
Gas3	Ammonium	4.6
Gas4	Carbon Dioxide	1.0
Gas5		0.0
Gas6		0.0

View | Enter-edit Esc-Exit

Fig. 7: Data entry form "Chemistry" for the region.

Enter data about the city emission sources: 12 sources entered

Source Number	1			Emission Rate (m3/s)	225.90
Height (m)	200	X coord.(km)	2.25	Emission Temperature (C)	138.0
Diameter (m)	8.1	Y coord.(km)	3.50	TSP Separation Ratio (%)	0
TSP Emission Mean (Kt)		0.500	TSP Emission Max (g/s)		40.3
Gas1 Emission Mean (Kt)		25.600	Gas1 Emission Max (g/s)		990.0
Gas2 Emission Mean (Kt)		1.150	Gas2 Emission Max (g/s)		312.0
Gas3 Emission Mean (Kt)		0.000	Gas3 Emission Max (g/s)		0.0
Gas4 Emission Mean (Kt)		0.000	Gas4 Emission Max (g/s)		0.0
Gas5 Emission Mean (Kt)		1.334	Gas5 Emission Max (g/s)		107.5
Gas6 Emission Mean (Kt)		0.000	Gas6 Emission Max (g/s)		0.0

View | ↓-Next ↑-Prev Enter-Edit Ins-Insert Del-Delete Esc-Exit

Fig. 8: Data entry form "Sources" for the city.

Emission sources data

Sample "Sources" data entry forms for the city and the region are presented in Fig. 8 and Fig. 9, respectively. These forms include a standard set of parameters about each chimney to be considered. In the case of the city, the maximum emissions values should also be included.

Each new source entry is initiated by depressing the (Ins) key on the keyboard. The total number of sources entered is indicated in the upper right-hand corner of the screen. Up to 300 sources can be entered into the database; they can be reviewed and/or modified when the data entry procedure is complete.

Landscape data (SIGMA matrix values)

After the geographical data has been entered, the SIGMA matrix – used to store landscape data – is filled with the average estimations of the relative danger coefficients. These values are derived from the average population density for the area.

The "SIGMA" data entry form is depicted in Fig. 10. Using this form, the values can be corrected, adjusting them to the particular landscape. This is usually necessary only when estimating economic damage to certain area cells.

In the "SIGMA" multiple data entry forms, one form represents one line of the matrix. Because the array of SIGMA values can be as large as 35 × 35, the total array cannot be presented on the screen at once. Several lines of data can be entered sequentially, saved using the (F2) key, and corrected later for particular case study.

Before exiting the form, the system prompts:

Update the file?

If the user responds with NO, the modified data will not be updated!

Enter data about the regional emission sources: 11 sources entered

Source Number 1 Emission Rate (m3/s) 97.00

Height (m)150 X coord.(km) 17.40 Emission Temperature (C)220.0

Diameter (m) 4.0 Y coord.(km) 52.70 TSP Separation Ratio (%)90

TSP Emission Mean (Kt) 1.400

Gas1 Emission Mean (Kt) 18.000

Gas2 Emission Mean (Kt) 8.000

Gas3 Emission Mean (Kt) 0.000

Gas4 Emission Mean (Kt) 6.000

Gas5 Emission Mean (Kt) 0.000

Gas6 Emission Mean (Kt) 0.000

View | ↓-Next ↑-Prev Enter-Edit Ins-Insert Del-Delete Esc-Exit

Fig. 9: Data entry form "Sources" for the region.

Enter Correct Landscape and Population Density matrix: 9 lines entered

Successively enter current matrix row # 1

Col. 1 0.90	2 0.90	3 0.90	4 0.90	5 0.90
Col. 6 0.90	7 0.90	8 0.90	9 0.90	10 0.90
Col.11 0.90	12 0.90	13 0.00	14 0.00	15 0.00
Col.16 0.00	17 0.00	18 0.00	19 0.00	20 0.00
Col.21 0.00	22 0.00	23 0.00	24 0.00	25 0.00
Col.26 0.00	27 0.00	28 0.00	29 0.00	30 0.00
Col.31 0.00	32 0.00	33 0.00	34 0.00	35 0.00

View | ↓-Next ↑-Prev Enter-Edit Ins-Insert Del-Delete Esc-Exit

Fig. 10: Data entry form "SIGMA".

Pollution Estimation

Emission distribution, economic damage and pollutant transport estimations are calculated during this phase. The calculation runs should be performed only after all data preparation has been finished completely. During the calculation runs, comments reporting the current status of the calculations appear on the bottom line of the screen.

Several means of validating that the data are consistent and meaningful are incorporated in the system. Messages reporting the current status and intermediate results are displayed on the user's screen. If error messages appear, the user should select the "Show results" option in the system's main menu for clarification of the situation.

The following types of error can be identified:

Error 1: Check the step of the regular grid.
Regular grid steps should be within the range 0.5–2 km for cities and 5–10 km for regions.

Error 2: Check average population density.
The population density should be within the range 10–30,000 persons per km^2.

Error 3: Check mean annual surface air temperature.
The mean annual surface air temperature should be within the range 0–30 °C

Error 4: Check surface air temperature in July/January.
Surface air temperature in July/January must be in the interval $-40, \ldots, 40$°C.

Error 5: Check annual surface wind speed.
Annual mean wind sped should be within the range 0.5–10 m/s.

Error 6: Check surface wind reiteration.
The sum of all the wind reiteration values should be equal to 1.

Error 7: Check MOPC and aggressiveness for the X.
There is a difference between the number of MOPCs and the number of aggressiveness coefficients entered for pollutant X.

Error 8: Unacceptable aggressiveness for the X.
The aggressiveness coefficient of pollutant X is less than 1.

Error 9: Unacceptable MOPC value.
MOPC values should be greater than 0.

Error 10: Check diameter! Source #N.
The diameter value for source N should be within the range 0.3–50 m.

Error 11: Check emission temperature! Source #N.
Emission temperatures for source number N should be within the range 0–600 °C.

Error 12: Check emission rate! Source #N.
Emission rates for source number N should be within the range 0.01–2000 m^3/s.

Error 14: Check X-coordinate! Source #N.
X-coordinate is not within the area of the source N.

Error 15: Check Y-coordinate! Source #N.
Y-coordinate is not within the area of source N.

Error 16: There are no emissions for the X.
At least one pollutant emissions data should be entered if one wants to have useful results.

Error 17: Check annual emission! (Source #N for X).
Only one annual emission or maximum emission of pollutant X for source N has been entered. The situation can happen only for the city and it means that one should enter both data values.

Error 18: Check annual and maximal emissions! Source #N for X.
There is discrepancy between average and maximal emission values. The average emission, represented in g/s, is greater than maximum emission value for pollutant X in source N.

Error 19: Unacceptable SIGMA value!
All SIGMA values must be within the range 0.05–30.

Error 20: Check wind reiterations in the mixing layer.
The sum of all the wind reiteration values in the mixing layer should be equal to 1.

Error 21: Check annual wet period ratio.
The wet period ratio should be within the range 0.07–0.15.

Error 22: Emission variation value is not correct! Source #N for X.
The value should be in the interval (−100,...,100%).

Error 23: Wrong information about new source #N!
New parameters should be entered for the source allocated.

The following errors may occur when optimization begins:

Error 24: Source #N has been included in the measure twice.
Check information about measures and remove redundant references to the sources mentioned.

Error 25: Emission decrease for pollutant X in group M exceeds 100%!
There is not enough information in the matrix of alternatives or some initial measures data is not correct.

Error 26: Wrong information about investments.
Investment values are less than zero.

Error 27: Measure is indefinite.
There are errors in the measure or group numbers.

Technological Measures Simulation

Technological measures are defined and entered into the system during the technological measures simulation phase. Accuracy is of utmost importance in the formulation of these measures by the user. The data forms presented in Fig. 11 are intended to be an aid in entering the appropriate data and carrying out the technological measures simulation.

The inherent feature in this phase is to remember which source – new or old – is to be included. The forms may be used many times sequentially. This is interpreted as being equivalent to carrying out measures for several sources simultaneously.

The method for entering new source parameters into the form is similar to the method described on page 7 for entering source data. The measures for the old sources are described for the system by the variations in their emissions (in %). The value should be entered with a "−" or "+" sign, designating a decrease or increase in emissions, respectively. Other parameters of the old sources may be entered together with new values, (height, diameter, etc.), but this is rarely required.

While the form is being modified, help and comments are visible on the bottom line of the menu screen. After the measure has been updated, the system will pause while data checks are made. The user should correct all errors reported by the system. The list of errors may be printed out using the "Print results" option in the system's main menu. When the data is error-free, the measure is simulated by many criteria.

At the end of the simulation, the user is prompted to enter a new measure.

Enter technological measures for the region sources: 2 sources entered

New allocated source numbers MUST be greater than max existing source number
and new full parameters set MUST be entered for them.
Annual emission variations in % MUST be given for existing sources.

Source # 5

TSP Emiss. or Em.Var.-100.000	TSP Sep.Ratio (%) 0
SO2 Emiss. or Em.Var.-100.000	Height (m) 0.0
NOx Emiss. or Em.Var.-100.000	Diameter (m) 0.00
Gas3 Emiss. or Em.Var. 0.000	Temperature(C) 0
Gas4 Emiss. or Em.Var.-100.000	Rate (m3/s) 0.0
Gas5 Emiss. or Em.Var. 0.000	X coord. (km) 0.000
Gas6 Emiss. or Em.Var. 0.000	Y coord. (km) 0.000

View | ↓-Next ↑-Prev Enter-Edit Ins-Insert Del-Delete Esc-Exit

Enter technological measures for the region sources: 2 sources entered

New allocated source numbers MUST be greater than max existing source number
and new full parameters set MUST be entered for them.
Annual emission variations in % MUST be given for existing sources.

Source # 12

TSP Emiss. or Em.Var. 1.500	TSP Sep.Ratio (%)95
SO2 Emiss. or Em.Var. 8.000	Height (m) 300.0
NOx Emiss. or Em.Var. 6.000	Diameter (m) 10.00
Gas3 Emiss. or Em.Var. 0.000	Temperature(C) 150
Gas4 Emiss. or Em.Var. 7.000	Rate (m3/s) 100.0
Gas5 Emiss. or Em.Var. 0.000	X coord. (km) 43.000
Gas6 Emiss. or Em.Var. 0.000	Y coord. (km) 35.000

View | ↓-Next ↑-Prev Enter-Edit Ins-Insert Del-Delete Esc-Exit

Fig. 11: Data entry form "Technological Measures Simulation".

Decision Optimization

When all measures have been entered into the system, the user may begin the decision optimization phase. It might be the case that alternative measures that cannot be implemented simultaneously occur within some measures group (see Section 2.1.4 of the *IPAC System Handbook*). Using the alternative measure "Pairs" data entry form, these measures can be identified. If no alternative measures exist in the groups formed, this step may be omitted.

A number of data checks are performed during the initial stages of optimization (emissions by each measure entered for each group, etc.). If errors are identified, the calculations stop and the user should correct the errors.

When the data is error-free, single and multicriteria optimization begins. The name of the criterion being optimized and the the current status of the calculations are reported at the bottom of the user's screen.

Optimized Measures Set Definition

The results of the decision optimization phase can be found in the "Show results" selection of IPAC's main menu (sub-menu "Listings" under the title "Multicriteria Optimization"). The listing contains optimal strategies sorted according to the preferences formulated by the algorithmic rules of the IPAC system. Each of these strategies is described by the summarized "cost-effect" parameters. The "criterion number" for each strategy is known. It is the key to the optimal set formulation.

The user should choose the strategy that he prefers and that meets his expectations. Since several strategies are possible, he should remember their "criterion numbers" and the corresponding estimations of investments. This information should be entered into the data entry form that appears when the user selects the "Optimized measures set definition" item in the system's main menu.

An in-depth analysis of the situation in the modelling area requires a thorough study of the results prepared by the IPAC system. These results can be viewed on the screen or printed.

Show results

The results provided to Decision Makers by the IPAC system can be divided into four main categories:

1. *Three-dimensional maps* that present spatially-distributed data for the raster grid. The numeric values of the distribution data can be found in the corresponding listings (emissions, economic damage and concentrations, depositions, etc.).

2. *Graphs* that present optimization results by each criteria used. These graphs can be especially useful if particular problems of atmospheric protection are expressed and emphasized.

3. *Data lists* that present the results of system runs for analysis by the user. Both final data as well as the initial data entered by the user can be found in these lists.

4. *Listings of the optimal measure sets*, prepared after the multicriterial optimal strategies have been selected by criterion number and investments volumes. These listings can be prepared after graphical analysis if data about criterion number and investments, or criterion number and percent pollution decrease are identified.

Printing Results

All the data described in the previous section can be printed out using the "Print results" option of the system's main menu. The sub-menus are arranged in the same way as the "Show results" submenus.

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System Handbook

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IPAC: Industrial Planning Air Control System

System Handbook

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IPAC, version 1.0, was developed for the Department of Industrial Operations, Industrial Planning Branch, of the United Nations Industrial Development Organization (UNIDO).

1 Introduction

The IPAC System is a software system designed for deci... support in problems of atmospheric protection and air quality management for industrial planning on national, sectoral and enterprise levels. It can be used within areas up to 400 × 400 km (approximately 300 × 300 miles). The system can be applied to a variety of industrial areas, cities and relatively small states. The following features of the system can prove useful in various applications:

- database of stationary pollution sources;
- database of technological measures (e.g. optional filters, fuels, liquidation of emission source, etc.);
- data on industrial and source-specific impacts on the atmosphere;
- ecological and economical effectiveness analysis of industrial innovations;
- optimized investment allocations for air quality protection;
- maximum resource calculation required for atmospheric protection options;
- air pollution minimization within the specified expenditures;
- definition of effective set of measures that could be applied to each emission source.

Solutions can be calculated simultaneously for a given set of pollutants.

The system requires minimal data input for its runs, taking into consideration the application environments in the developing countries. Most of these data are widely available from statistical books and special publications. Where possible, default data have been provided in IPAC.

Data input is supported by a set of menus and on-line help. Samples of input data can be found in the documentation, along with a clear explanation of the overall structure of the package. The interface is user-friendly and easy to use for inexperienced users. Interactive work with the system is supported by on-line explanations and illustrations.

The following data sets are required for system runs:

- emission source data (height, diameter, coordinates, gas temperatures and volumes, annual and maximum emissions);
- measure data (investments and operational costs, emission changes by each pollutant);
- meteorological data as averaged for ten or more years (annual air temperature, speeds and probabilities of surface and boundary winds, height of boundary layer, air stratification and turbulent parameters);
- physical and chemical parameters (dry deposition speeds, wet deposition coefficients, lifetime of SO_2, NO, NO_2, sulfates and nitrates).

The following types of data and maps are available to the decision maker at the end of a run:

- maps of emission distribution;
- maps of economical damage distribution;
- maps of pollutant concentration distribution;
- maps of wet and dry deposition sulfates and nitrates;
- sulfate and nitrate transportation diagrams out of the area considered;
- maps evaulating danger (through acid rain) to coniferous forests;
- graphs of optimal strategy as a function of expenditures for atmospheric pollution reduction by each selected criteria (emissions, concentrations, depositions, transportation out of the region, danger to coniferous forests) and any combination thereof.

The system is directed toward a wide range of applications and user groups, including city councils and regional management offices, industrial enterprise management, state governments and business management schools. The package was tested and used in a number of countries, including the USSR, Bulgaria and the GDR. A variety of regions with different geographic and climatic conditions were used as test fields.

A number of new models and subsystems intended to expand the capability of IPAC as an analysis and decision support system (DSS) tool are under preparation. These include:

- car and traffic impact analysis;
- surface water DSS;
- resource distribution for atmosphere and water quality protection.

The IPAC system currently runs on IBM PC/DOS and compatibles. A UNIX version is also to be developed for running on the PC/386 and workstation environments.

2 System Data Information

The initial information required by the IPAC system could be divided into two parts. The *user data* consists of concrete data on a city/region, which the user should take some care in preparing if he intends to obtain useful results.

The *default data* consists of parameters that the user might be unaware of when he starts the case study. The values that have been assigned to these parameters were defined during long-term studies based on real applications. In order to correct these parameter values, one should have a clear and deep knowledge of atmospheric physics and chemistry, as well as complex system simulations experience. Users interested in obtaining a better understanding of the details and mathematical formulae of IPAC are encouraged to read this section.

2.1 User Data

The complete set of user data necessary for system runs is presented in Table 2.1.

2.1.1 Characteristics of the raster grid representing a city/region

The name of the simulated city/region should be entered into the system by the user. The area must be represented by a regular grid (i.e. a rectangle divided into square cells), as shown in Fig. 2.1. Three parameters characterize the regular grid:

- number of raster cells along the X-axis (from West to East),
- number of raster cells along the Y-axis (from South to North),
- size of raster cell (regular grid step), in km.

The origin (0,0) of the coordinate system is located in the lower left-hand corner of the grid. The simulated area (rectangle) could be larger than is necessary for the city/region. Usually a step size of up to 1 km is considered for a city, up to 10 km for a region. This implies 35 x 35 km cities and 350 x 350 km regions – sizes convenient for most applications.

NOTE: *The regular grid size must not exceed* 35 x 35 *(1225 cells total).*

The average population density can easily be calculated. In geographical atlases one can find the area of the city/region as well as the number of people living there.

The maximum number of pollutants for IPAC-UNIDO is seven. One of these pollutants is always TSP (Total Suspended Particulars) and up to 6 gases are allowed.

The selection of the necessary gases can be made by the user, but this is not an easy task. One should know the particular situation in the city/region. No common universal advice can be given for this case, but some general comments may prove useful:

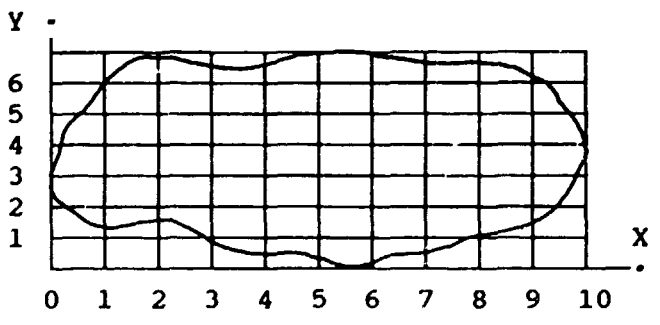


Fig. 2.1: Presentation of city or region in the IPAC system.

Table 2.1: User data necessary to run IPAC.

1. Characteristics of the raster grid representing a city/region
   - 1.1. Name of city/region
   - 1.2. Simulation site size (number of raster elements from West to East and from South to North)
   - 1.3. Grid spacing (raster element size), km
   - 1.4. Average density of population, per km^2
   - 1.5. Number of pollutants included in IPAC system
   - 1.6. Agressiveness coefficient of each pollutant
   - 1.7. Landscape map of the city/region
   - 1.8. Maximum occasional permissible concentration for each pollutant (only applicable to city)
2. Meteorological characteristics
   - 2.1. Mean annual surface air temperature, °C
   - 2.2. Mean annual surface wind speed, m/s
   - 2.3. Mean annual surface wind reiteration within 8-point wind rise (only applicable to region)
   - 2.4. Mean annual precipitation, mm/year
   - 2.5. Average number of wet days in a year
   - 2.6. Mean annual height of mixing layer, m
   - 2.7. Mean annual wind reiteration in the mixing layer within 12-point wind rise (only applicable for city)
   - 2.8. Surface air temperature in July/January at 1 p.m., °C
3. Emission source parameters (individual for each source)
   - 3.1. Height, m
   - 3.2. Diameter, m
   - 3.3. Emission rate, m^3/s
   - 3.4. Emission temperature, °C
   - 3.5. Mean annual emission of pollutants (individual for each pollutant), 10^3 t/yr
   - 3.6. Source coordinates, km
   - 3.7. Dust removal coefficient, %
   - 3.8. Maximum pollutant emission (individual for each pollutant), g/s (only applicable to city)
4. Technological and economic characteristics of atmospheric protection activities (individual for each type of activity
   - 4.1. Capital outlays required to implement the activity, 10^3 monetary units
   - 4.2. Total expenses required to implement the activity, 10^3 monetary units
   - 4.3. Changes in pollutant emission after the implementation of the activity at each relevant source (% of the initial emission from the source)
   - 4.4. Changes in the other parameters (3.1, 3.2, 3.3, 3.4, 3.6, 3.7) after the implementation of the activity at each relevant source (new values)
   - 4.5. Expert estimations to combine activities

- Pollutant selection is the most difficult problem for the city. At least three of the possible pollutant types are fixed for the IPAC system in the region version. These are TSP (it is still necessary to decide if it is toxic or not), SO_2 (sulfur dioxide), and NO_x (nitrogen oxide). The IPAC system allows the detailed study of sulfur and nitrogen in the atmosphere. For the other four pollutants, one can define only emission and economic damage estimations if they are included in the simulation.

- It is known that there are usually TSP, SO_2, NO_x, and CO pollutants in a city. This stems from the common industrial structure of cities, that includes energy plants, food and municipal services, metallurgy. However, it does not mean that pollution is always inherent for all the pollutants mentioned.

- There are very polluted cities for which pollutant selection is not a problem. If the number of pollutants to be considered exceeds seven, one should run the IPAC system more than once.

As one can see, the selection of pollutants is complicated in itself. But how can one find an efficient strategy for atmospheric protection for an area when costs must also play a role? Let us suppose the pollutants have been chosen. Using Table 2.2 one can find the aggressiveness ratio that is used to compare the given pollutant impact to CO aggressiveness. The latter was assigned a ratio equal to "1". In the table, the coefficients of the major chemical compositions that could pollute the atmosphere in industrial areas are listed. The total number of these options reaches into the thousands.

The aggressiveness coefficient evaluation method is presented in Section 4.4. Here we point out that the maximum occasional permissible concentrations (MOPCs) and the maximum permissible concentrations (MPCs) for the USSR were considered while calculating the necessary coefficients. These concentrations are usually national standards, so one can find the appropriate concentrations in reference books and correct the aggressiveness coefficients against them if necessary.

Let us suppose the following:

- $N_{CO}^{(1)}$ and $N_{CO}^{(2)}$ are the national standards selected for the CO MOPCs and the CO MPCs (mg/m^3);

- $N_k^{(1)}$ and $N_k^{(2)}$ are the same but for the k-th pollutant;

- $P_k^{(1)}$ and $P_k^{(2)}$ are the values from Table 2.2 (3-rd and 4-th columns).

Then

$$A_k^{new} = \frac{N_{CO}^{(1)} \times N_{CO}^{(2)} \times P_k^{(1)} \times P_k^{(2)} + 60 \times N_k^{(1)} \times N_k^{(2)}}{N_k^{(1)} \times N_k^{(2)} P_k^{(1)} \times P_k^{(2)}} \qquad (2.1)$$

NOTE: *If the calculations are being made for a city, then the MOPC for the pollutants selected should be taken from Table 2.2 or from national standards.*

2.1.2 Meteorological characteristics

All meteorological data are defined as the average arithmetic mean for a period of at least 10 years. This should average possible weather deviations that could occur during some years. Meteorological data necessary for IPAC system simulation runs can be found in climatic reference books and regional hydrometeorological services.

While preparing the data, the following should be kept in mind:

- the average surface temperature should be measured in °C;

Table 2.2: Maximum permissible concentrations (MPCs), maximum occassional permissible concentrations (MOPCs), and agresssiveness coefficients of some atmospheric pollutants.

Agent	Aggressiveness ratio	MPC mg/m^3	MOPC mg/m^3
Carbon monoxide	1	3	20
Sulfuric anhydride	22	0.05	10
Hydrogen sulfide	54.8	0.008	10
Sulfuric acid	49	0.1	1
Nitrogen oxides (by NO_2)	41.1	0.04	2
Ammonia	10.4	0.04	20
Low-molecular hydrocarbons (by carbon)	3.16	1.5	100
Acetone	5.55	0.35	200
Methylmercaptan	2890	$9 \cdot 10^6$	0.8
Phenol	310	0.003	0.3
Acetaldehyde	41.6	0.01	5
3,4-benzpyrene	$12.6 \cdot 10^5$	10^{-6}	$1.5 \cdot 10^{-4}$
Hydrogen cyanide	282	0.01	0.3
Hydrofluoric acid and other compounds of fluorine	980	0.005	0.05
Chlorine	89.4	0.03	1
Aluminum oxides	33.8	0.15	6
Silicon dioxide	83.2	0.05	1
Carbon black (without other compounds)	41.5	0.05	4
Oxides of sodium, magnesium, potassium, calcium, iron, strontium, molybdenum, tungsten, bismuth	15.1	0.15	10
Woody dust	19.6	0.15	6
Wanadium pentoxide (dust)	1225	0.002	0.5
Inorganic compounds of 6-valencychronium (by C_4O_3)	10^4	0.005	0.01
Manganese and its oxides in aerosol (by Mg)	7070	0.001	0.03
Cobalt and cobaltic oxide	1730	0.001	0.5
Nickel and its oxides	5475	0.001	0.05
Zinc oxide	245	0.05	0.5
Arsenous oxides (by As)	1581	0.003	0.2
Inorganic compounds of mercury (by Hg)	22400	0.0003	0.01
Inorganic compounds of lead (by Pb)	22400	0.0003	0.01
Ashes of black diamond (average)	–	–	80
Ashes of peat (average)	–	–	60
Ashes of coke and agglomeration dust from metallurgy (average)	–	–	100
Coal dust	–	–	40
Dust of nickel agglomerate	–	–	600
TSP of diesel and of the marut-combustion engines	–	–	200
Dust of cement plants (average)	–	–	45
Micaceous dust	–	–	70
Talc dust	–	–	35
Limestone and gypsum dust	–	–	25

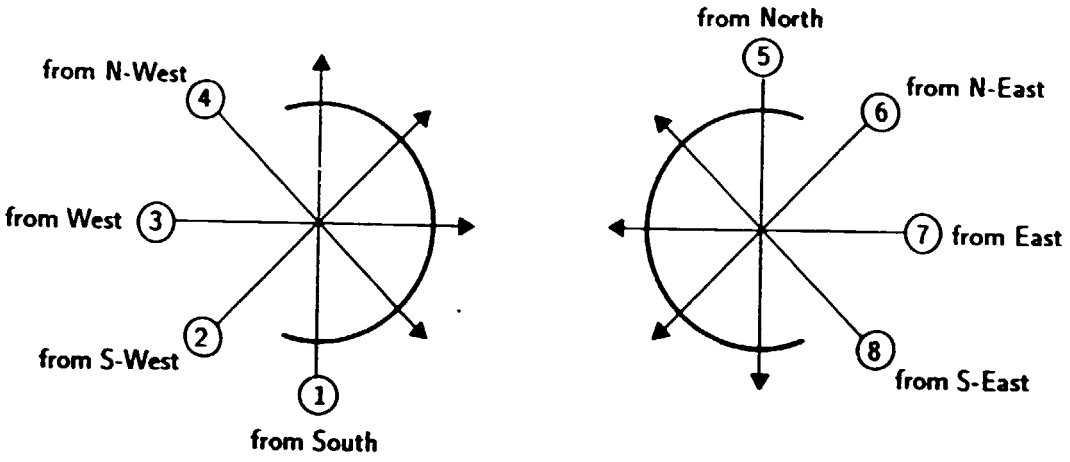


Fig. 2.2: Wind directions considered in the IPAC system.

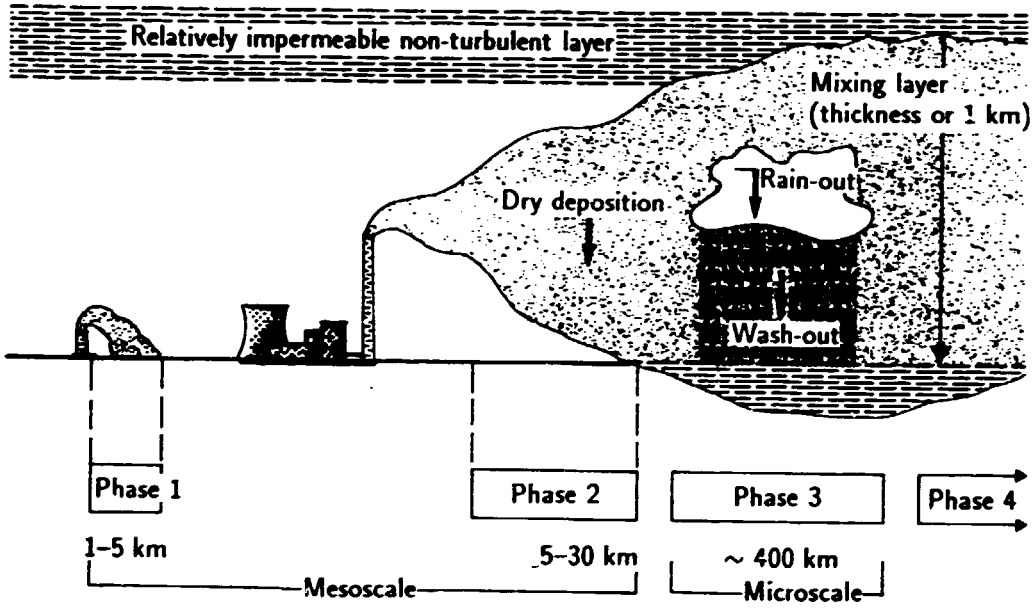


Fig. 2.3: The pollutant transportation process from the plume.

- the average surface wind speed should be measured in m/sec;
- the average surface wind speed reiteration should be defined by 8-directions. In references, such data are either presented dimensionless or as percents. The former is true in the IPAC system.

For the wind directions considered in the IPAC system, it is assumed that the first direction is the "northern wind" from the South to the North (see Fig. 2.2). Meteorological data should provide additional information depending on the type of area (city/region) under consideration. In the case of a city, it is necessary to define the average annual temperature of the coldest or warmest month in °C. The appropriate data, by years and by months, can be found in climate reference books. If there are many power plants in the city, the average temperature for January is usually used, as these plants use various fuels and have their maximum emissions during the cold season. If the energy industry impact is not the major one, the average temperature for July is used.

Chemical pollutants and the products of their chemical reactions are transported for several hundred kilometers by winds. This usually occurs in the so-called "boundary" or "mixing" layer – the layer of atmosphere extending from the earth's surface to a height of 1000 m. The pollutant transportation process from the plume is depicted in Fig. 2.3. Pollutants are transported up to 400 km at phase 3 for several dozen hours. During this process they interact with the earth's

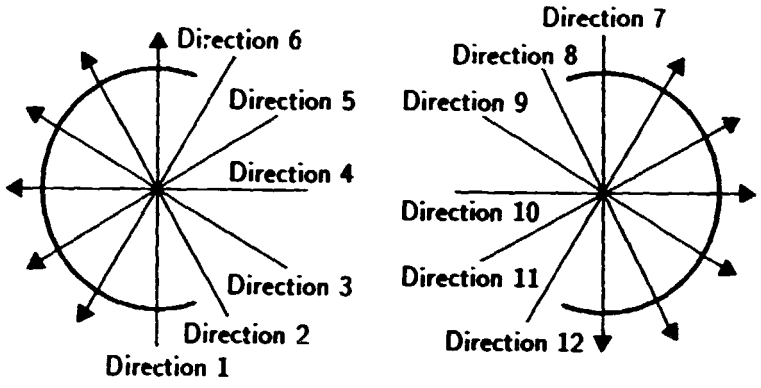


Fig. 2.4: Boundary wind speed directions in the IPAC system.

surface (dry depositions) and are washed out. Therefore it is important to have information on precipitation and the boundary layer. The following should be kept in mind:

- the annual average precipitation is considered in mm;
- the annual wet days ratio is a dimensionless value, less then "1", which is considered as the part of a year of 365 days;
- the average annual wind reiteration is measured in m;
- the average wind reiteration values for the boundary layer, described by the 12-directions, are less than 1.

Wind directions for the boundary layer are considered counter-clockwise by 30° starting from the the "northern wind" from the South to the North, as shown in Fig. 2.4.

2.1.3 Emission source parameters

Each chimney or emission source in the simulated area should be characterized by a set of data. These data are as follows:

- *Geometric characteristics* (height of chimney in m, its outlet diameter in m, coordinates of the source within the area).

  "Chimney outlet" is a generalized term. Some "chimneys" are of a rather arbitrary form, say the entire roof of a plant-section, etc. In such cases it is necessary to calculate the outlet diameter by representing the chimney as a circle of the the same area.

  The source's coordinates can be easily calculated. If the chimney is round, an error of several meters in the estimation of its coordinates is insignificant. However, when the "chimney" is a roof 100 m long the situation is more complicated. For the IPAC system, the geometric center of the appropriate figure should be considered in such cases.

- *Emission characteristics* (gas emission rate in m^3/sec, its temperature in °C, and average annual pollutant mass emissions in 10^3 t).

Chimney emission parameters are directly related to the technological processes in particular industries.

NOTE: (1) *If one of the simulated pollutants is TSP, it is necessary to estimate (in %) the TSP separation ratio for the given chimney. The size of the emitted particles is dependent on the value of this ratio and consequently influences the results of the TSP dissipation calculations.* (2) *If the calculations are being done for a city, in addition to the annual emissions averages one must prepare data on maximum emissions (in g/sec). In this case one should consider not emergency cases but maximum deviations that could happen under normal conditions and could take place during a relatively short period of time. It is commonly known that every industrial enterprise operates in such a way that it is impossible to point out absolutely stable and correct data. Variations in the types of raw materials, fuels, production output, etc., may always be present. Each enterprise has its own particular type of work and method of keeping data on emissions. These points should be taken into consideration when the maximum emissions are calculated. These emissions never equal the annual averages, but usually exceed it by a factor of 1.5–3, especially for such well-known pollutants as SO_2, NO_x, and CO.*

The geometric and emission characteristics mentioned above can usually be found in special municipal books or in books on national statistics reports, if there is an emissions monitoring service in the country. If these data are nonexistent, it may be that the atmospheric pollution problem in the given area has not yet been formulated. In such cases, only general intuitive considerations like "clean air is better than polluted air" can apply. Monitoring and measurement services should be established to identify and formulate problems before the IPAC system is applied.

The necessary information can be gathered in a number of ways, some simpler and more cost-efficient than others. For example, in one case the chimney geometry might be calculated using its shadow. The estimation of emission parameters, however, is somewhat more complicated. There are two ways of finding a solution – through relatively simple measurements, or using engineering methods based on the technologies used.

Thus, the main problem of finding information about the sources lies not in the definition of source parameters, but in the estimation of the quantity of sources to be included in IPAC system runs. There are thousands of chimneys in cities and regions, most of which are small sources of emission. So, for example, of the 1500–2000 chimneys present in a city of population around 500.000, only 50–100 chimneys could be considered as large sources of emission. Consequently, small sources are aggregated into equivalent large ones – a method widely used in research and simulation.

Small emission source aggregation on a regular grid with a small step The first question is obvious: what is considered to be a small source of emission? In the case of a city, there is no uniform answer because there is no single parameter that can identify the size of the emission source. Nevertheless, one could say that a source is small if the following properties are met:

- small emission sources are usually about 20–25 m high;
- they consume relatively low quantities of fuel or coal (up to 700–800 tons per year);
- classical pollutant emission levels (nontoxic TSP, SO_2, NO_x, CO) are relatively low (less than 0.01% of the total emissions in the city);
- small emission sources can often be liquidated and their functions transferred to larger enterprises making it senseless to invest in new technological emission reduction measures;
- in many cases, small emission sources are the section hatches in the roofs of enterprise buildings;

- many small emission sources are fuel furnaces of homes, municipal services, and public utilities.

If small sources have been identified, they should be aggregated into several equivalent large ones. A group of small sources can be aggregated into one if:

- the maximum or minimum source coordinates vary by not more than $\approx 1/5$ of the regular grid step (i.e. by 200 m when the grid step is 1 km); this produces errors during calculation within 20–25%, which is acceptable for the IPAC system;
- the maximum and minimum heights of the sources differ by less than 10 m;
- the maximum and minimum emission rates differ by less than a factor of 2;
- the maximum and minimum emission temperatures differ by less than a factor of 1.5.

The corresponding emission source parameters for this case are as follows:

$H_E = (H_{\min} + H_{\max})/2$ – height,

$D_E = (D_{\min} + D_{\max})/2$ – diameter,

$V_E = (V_{\min} + D_{\max})/2$ – emission rate,

$T_E = (T_{\min} + T_{\max})/2$ – emission temperature,

$X_E = (X_{\min} + X_{\max})/2$ – X-axis coordinate,

$Y_E = (Y_{\min} + Y_{\max})/2$ – Y-axis coordinate,

$F_E = (F_{\min} + F_{\max})/2$ – TSP separation ratio (if there is a TSP emission release),

$M_E^A = \sum_{i=1}^{n} M_i^A$ – average yearly emission for the n aggregated sources,

$M_E^M = \sum_{i=1}^{n} M_i^M$ – maximum emission for the n aggregated sources.

Small emission source aggregation in the region on a regular grid with an averaged step A chimney 50 m high can be considered a small one. This feature is associated with the meso-scale transport model of sulfur and nitrogen compositions in the IPAC system. It is recommended to aggregate small emission sources for each regular grid raster. The corresponding emission source parameters for this case are as follows:

$H_E = 50$ m – height,

$D_E = (D_{\min} + D_{\max})/2$ – diameter,

$V_E = (V_{\min} + D_{\max})/2$ – emission rate,

$T_E = (T_{\min} + T_{\max})/2$ – emission temperature,

$X_E = (X_{\min} + X_{\max})/2$ – X-axis coordinate,

$Y_E = (Y_{\min} + Y_{\max})/2$ – Y-axis coordinate,

$F_E = (F_{\min} + F_{\max})/2$ – TSP separation ratio (if there is the TSP emission release),

$M_E^A = \sum_{i=1}^{n} M_i^A$ – average yearly emission for the N aggregated sources.

The notation in the formulae corresponds to the above-mentioned.

NOTE: *One should remember that the number of aggregated sources in the IPAC system cannot exceed 300. The resulting sources should be enumerated after aggregation.*

2.1.4 Technological and economic characteristics of atmospheric protection activities

Suppose for a city there is a set of sources and the corresponding set of parameters. These data are used in the IPAC system to estimate atmospheric air pollution. Thus data prepared according to the specifications of section 2.1.3 describe the regional air pollution situation. Any new technological, economic or geographical innovation in the city/region leads to changes in some emission source parameters. If such changes are defined quantitatively and are technically feasible, it is considered by the IPAC system to be a "technological measure". "Quantitatively" means that the expenditure estimations for the measure's implementation as well as new emission source characteristics are known. "Technically feasible" means the possibilities for a measure's implementation for the given sources can be determined only by experts and only for measures defined quantitatively.

The general scheme for defining measures in the IPAC system is shown in Fig. 2.5. It provides a universal technique for analyzing new measures in regional or city industries.

The following data are necessary for each measure shown in Fig. 2.5:

- investments and annual costs;
- numbers of the sources whose characteristics changed (modified sources);
- characteristic variations by each source to be modified and defined as follows:
  - as percentage of the base level for annual and maximum pollutant emissions ("+" if the emission increases, "−" if it decreases),
  - as new values for the rest of the parameters, e.g. height, diameter, emission rate, temperature, TSP separation efficiency, coordinates;
- new source numbers, allocated at the city/region area when the measure is implemented;

  NOTE: *New source numbers should be greater than the last existing source number.*

- new source parameters, as described in Section 2.1.3.

This is the complete set of data about each technological measure in particular. No data are necessary for "simple" (from the simulation point of view) technological measures, e.g. the measures to be applied to the only existing city or regional source. In the case of new source allocation, one needs data only about the new sources.

The IPAC system provides unique possibilities to simulate any possible number of situations in a city/region while undertaking a variety of possible technological atmospheric protection measures. The price paid for achieving these benefits is the necessity to arrange the complete set of possible measures into groups to simplify the interpretation of calculation results. For example, one could group together sources by industry, by quantities of fuel used, etc.

NOTE: (1) *The only formal requirement is that all measures that refer to the same source should be included in one group.* (2) *The number of measures in one group should not exceed 15 and the total number of measures should not exceed 30.* (3) *For each measure the group number should be known as well as the measure number within the group.*

The IPAC system and its optimization subsystem analyze a variety of possible combinations of initial measures during the run. If measures from the same group cannot be implemented concurrently, this case should be explicitly pointed out. In order to do this, one should pair the numbers of the measures that cannot be implemented simultaneously. Usually these measures can be applied to the same source. The following are examples of incompatible measures:

- the conversion of boiler fuel to natural gas and the installation of sulfur filtering equipment;

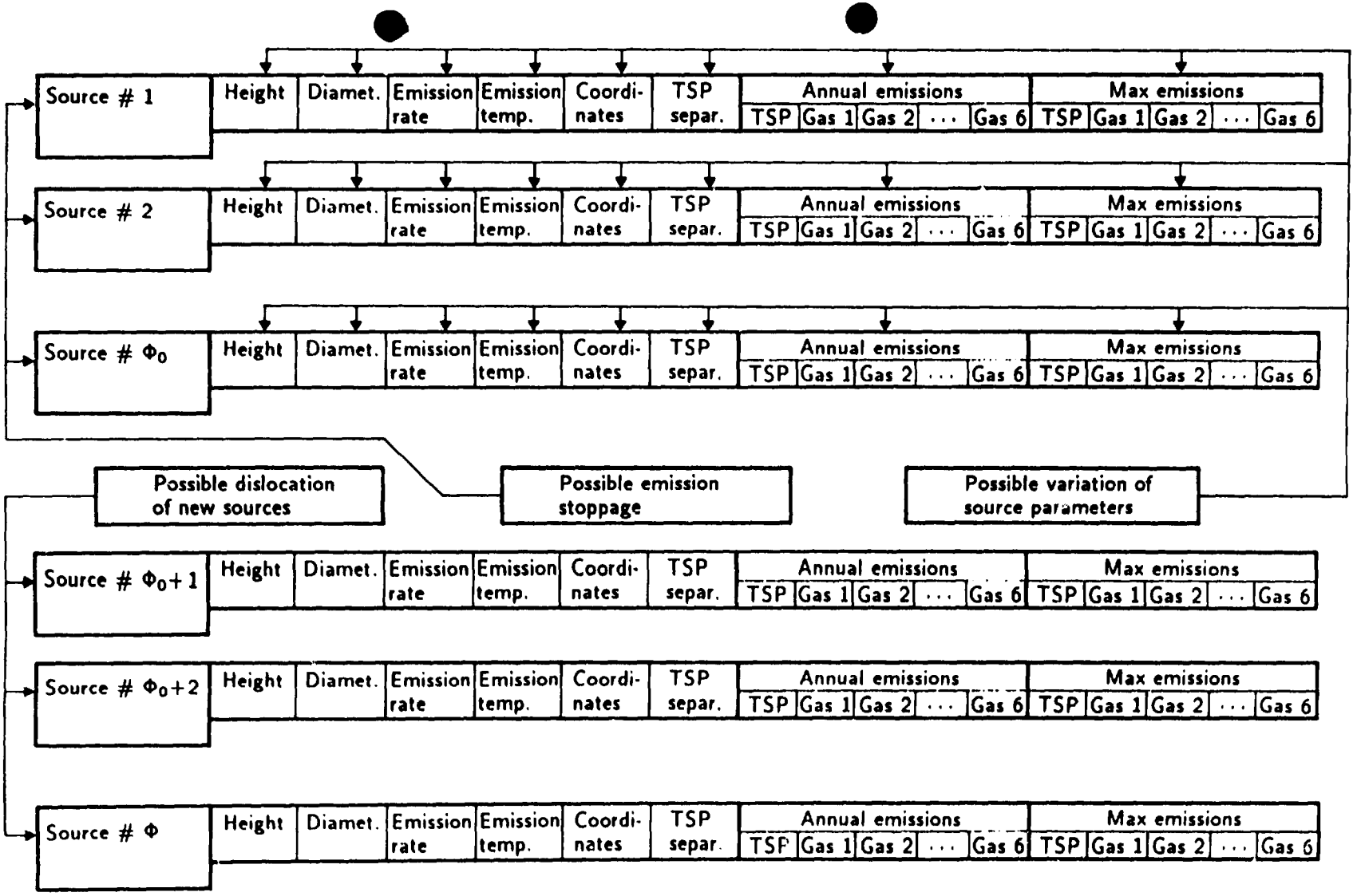


Fig. 2.5: Scheme for defining measures in the IPAC system.

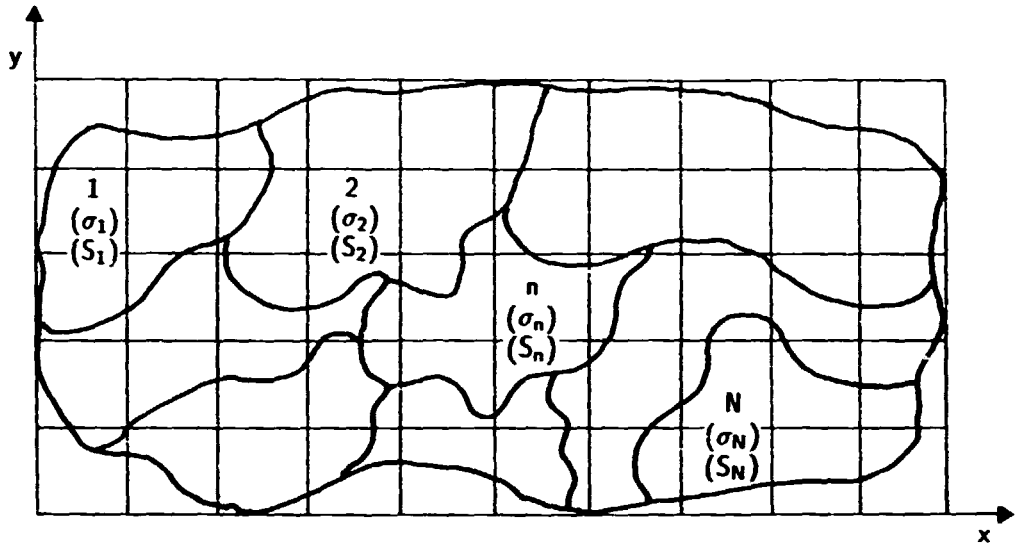


Fig. 2.6: Raster (i,j), where S_n is the raster area part occupied by the n-th recipient ($S_n < 1$), and σ_n is the table of values of the relative danger coefficient.

- for the same emission source, a power reduction by 10% and by 20%;
- liquidation of a source and the installation of new filtering equipment.

NOTE: *The maximum limitation of 450 initial measures (15 measures by 30 groups) could hardly be met in city simulations. Therefore, one should not aim at having the maximum group size. The optimal group size is about 8-12 measures.*

Nowadays, much is being published describing data about emission reduction measures for a number of industries. One can hardly recommend universal methods of defining the technical and economic characteristics of the available measures. Usually the most appropriate way to achieve the goal is to have experts who are familiar with the particular industries of the city/region simulate the atmospheric protection problems.

2.1.5 Landscape coefficient correction

Some σ_{ij} estimation is put into correspondence with each raster grid. This estimation shows the relative danger level of the air over the given raster. The calculated value of the estimation is dependent on the structure of the recipient in the given raster. In the other words, the value of σ_{ij} depends on the combinations of territory types within the given raster. For cities, the main recipient is the population. As the calculations are performed for a one-year period, one could assume that during this time interval the population density is the same for the whole city. Under this assumption, the average population density used for the estimation of the σ_{ij} coefficients is used in the IPAC system. For regions, where the population density is different and where the average σ_{ij} coefficients are calculated by the average population density, IPAC provides the option to correct the calculated matrix values. This option is available in both the city and the region versions.

Let us consider the σ_{ij} definition method for the regular grid raster (i,j). Suppose the raster area is equal to one. Using geographic maps of the city/region, one can define raster areas with different types of territories. Let us assume there are N types of territories in the raster (i,j), as illustrated in Fig. 2.6. Then

Table 2.3: Atmospheric air pollution estimation for the various types of territories.

Polluted area type	σ value
Recreation, sanatoriums, reserved areas, national parks	10
Country area, country housing	8
Urban areas with population density p persons/km^2	$0.001p$
Industrial areas	4
Forests	0.5–1.5
Agricultural areas (from South to North)	2–0.5
Gardens, wine production areas	3
Cattle areas, dry grass production areas	0.1–0.5

$$\sigma_n = \sum_{n=1}^{N} S_n \sigma_n, \tag{2.2}$$

where

$$\sum_{n=1}^{N} S_n = 1 \tag{2.3}$$

The values of σ_n are defined in Table 2.3.

NOTE: *For the central part of cities of population greater then 200,000, $\sigma = 8$ independent of the administrative density of the population.*

2.2 Default data

The set of data required for system runs and for estimating pollutant transport patterns, economic damage and coniferous forest danger includes meteorological, physical and chemical data that can be used for model adjustments. These data are presented in Table 2.4. Each parameter was analyzed by the possible variations interval. The intervals were defined through a careful analysis of published material and the results of experimental model runs.

Table 2.4: Default data of the IPAC system.

Model	Parameter	Value	Notation in Model
Meso-scale sulfur transport model (region)	SO_2 residence time in the atmosphere relative to chemical transformation into SO_4^{2-}	15 h	τ_0
	SO_2 dry deposition rate	0.015 m/s	ν_1
	SO_4^{2-} dry deposition rate	0.0025 m/s	ν_2
	Coefficient of SO_2 washout from the atmosphere	3.6 mm^{-1}	k_1
	Coefficient of SO_4^{2-} washout from the atmosphere	5.5 mm^{-1}	k_2
	Time interval	10 min	T
	Atmosphere stratification parameter	0.09	P_c
	Number of wind direction	48	m
	Accuracy of calculation	0.05	ϵ
Meso-scale nitrogen transport model (region)	NO residence time in the atmosphere relative to chemical transformation into SO_2	0.3 h	τ_1
	NO_2 residence time in the atmosphere relative to chemical transformation into PAN	40 h	τ_2
	NO_2 residence time in the atmosphere relative to chemical transformation into HNO_3 (OH− reaction)	15 h	τ_3
	NO_2 residence time in the atmosphere relative to chemical transformation into HNO_3 (H_2O− reaction)	20 h	τ_4
	HNO_3 residence time in the atmosphere relative to chemical transformation into NO_3^-	40 h	τ_5
	NO dry deposition rate	0.0007 m/s	ν_6
	NO_2 dry deposition rate	0.008 m/s	ν_7
	HNO_3 dry deposition rate (in gas)	0.015 m/s	ν_8
	HNO_3 and NO_3^- dry deposition rate (in aerosol)	0.003 m/s	ν_9
	Coefficient of NO_2 washout from the atmosphere	9.0 mm^{-1}	k_{10}
	Coefficient of HNO_3 washout (in gas) from the atmosphere	6.1 mm^{-1}	k_{11}
	Coefficient of HNO_3 and NO_3^- washout (in gas) from the atmosphere	6.1 mm^{-1}	k_{12}
	Portion NO_2 in NO_x emission	5%	-
	Concentrations O_3 surface atmosphere	30-50 ppb	-
Micro-scale pollutant transport model (city)	Dissipation coefficient	200	A
	Number of wind direction	36	m
	Accuracy of calculation	0.05	ϵ
Economic damage model	Average specific economic damage	2.4 \$/tce	γ
Coniferous forest model	Threshold value	6.0	$P^{(3)}$

3 Test Listings

Several test listings are presented in this section. The listings contain data on a city and a region. They represent the complete set of final data that the system can provide for a particular analysis. The data can be used for the system consistency tests and its presentations.

3.1 Data about a City

```
Greenfield

TOTAL number of sources:   12

-------------------------------------------------------------------------------------------------------
Wind directions  :  South     S-West      West       N-West      Nord       N-East      East       S-East

Reiteration      :  0.150     0.170      0.130       0.100      0.100       0.100      0.110       0.140
-------------------------------------------------------------------------------------------------------

Mean annual speed of the wind near the surface (m/s):          5.5
Mean annual air temperature                    (C):            5.0
Average air temperature in July or January     (C):           19.0

Regular grid parameters for the  city :
     The quantity of cells from the West to the East (X-axes):   9
     The quantity of cells from the South to the Nord(Y-axes):   6
     Grid step (km):                                             1.0
     Accuracy of the "SIGMA" calculation:                        4


Pollutant numbers upon which the data has been entered:  1  2  3  4  5  6

  Pollutant                 Agressiveness        MOPC

1. Cement Dust                   45.0          0.500000
2. SO2                           16.5          0.500000
3. NOx                           41.1          0.085000
4. NH3                            4.6          0.200000
5. HF                           980.0          0.020000
6. CO                             1.0          5.000000


"SIGMA matrix"
 Greenfield

   6    1.60  2.40  2.70  0.80  3.40  3.90  3.10  5.20  5.90
   5    4.00  4.00  4.00  6.20  7.80  6.30  4.60  4.20  3.40
   4    2.30  2.60  2.90  3.60  2.80  1.30  1.40  1.40  2.30
   3    1.60  0.50  0.80  3.10  3.60  2.30  2.70  2.80  4.30
   2    4.00  4.00  1.50  1.90  5.20  5.10  5.20  6.30  7.00
   1    4.00  3.60  1.30  1.80  4.20  4.60  5.00  4.10  3.20
          1     2     3     4     5     6     7     8     9
```

Information about the sources
Greenfield
Listing 1

Source number	Heig. m	Diam. m	Emiss. temp. C	Emiss. rate 3 m /s	Coef. SIGMA for sour.	TSP sep.	Total emission of pollutants, Ktons/year: TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	Source Coordinates,km: X	Y
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1.	200.0	8.1	138.0	225.9	3.47	0.0	0.500	25.600	1.150	0.000	0.000	1.334	0.000	2.25	3.50
2.	83.0	7.4	220.0	303.8	3.89	0.0	0.210	9.700	0.540	0.000	0.000	0.000	0.000	7.50	4.90
3.	103.0	4.8	200.0	81.7	3.49	0.0	0.054	1.200	0.100	0.000	0.000	0.000	0.000	5.70	2.10
4.	20.0	0.6	210.0	0.3	4.67	0.0	0.000	0.130	0.020	0.000	0.000	0.000	0.000	4.49	4.92
5.	20.0	0.3	200.0	0.5	1.95	0.0	0.070	0.090	0.010	0.000	0.000	0.016	0.000	2.67	1.83
6.	18.0	0.6	160.0	0.1	3.54	0.0	0.050	0.040	0.000	0.000	0.000	0.008	0.000	8.22	2.43
7.	15.0	0.5	45.0	0.0	1.40	0.0	0.600	0.600	0.000	0.000	0.000	0.140	0.000	6.46	3.81
8.	24.0	0.8	180.0	0.5	4.35	0.0	0.010	0.140	0.010	0.000	0.000	0.002	0.000	3.57	3.30
9.	102.0	2.0	45.0	19.4	3.18	0.0	0.000	9.700	4.300	0.000	0.000	0.000	0.000	1.50	5.16
10.	33.0	0.8	20.0	1.6	4.22	81.0	1.100	0.000	0.000	0.000	0.220	0.000	0.000	4.31	1.66
11.	30.0	0.4	20.0	1.5	4.30	0.0	3.200	0.000	0.000	0.000	0.000	0.000	0.000	5.12	3.87
12.	23.0	0.6	37.0	2.6	2.01	0.0	0.020	0.000	0.000	1.503	0.008	0.000	0.000	1.91	1.72
Total emission of pollutants in city							5.8	47.2	6.1	1.5	0.2	1.5	0.0		

Maximum emissions data
Greenfield
Listing 1

Source number	Max emission of pollutants, g/s: TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6
1	17	18	19	20	21	22	23
1.	40.30	990.00	312.00	0.00	0.00	107.50	0.00
2.	40.60	961.00	72.60	0.00	0.00	0.00	0.00
3.	10.10	560.30	18.40	0.00	0.00	0.00	0.00
4.	0.00	8.00	0.70	0.00	0.00	0.00	0.00
5.	3.70	4.90	0.40	0.00	0.00	0.80	0.00
6.	2.70	2.70	0.00	0.00	0.00	0.50	0.00
7.	3.90	3.60	0.00	0.00	0.00	0.90	0.00
8.	1.00	12.00	1.10	0.00	0.00	0.20	0.00
9.	0.00	304.60	132.40	0.00	0.00	0.00	0.00
10.	7.40	0.00	0.00	0.00	6.90	0.00	0.00
11.	62.20	0.00	0.00	0.00	0.00	0.00	0.00
12.	3.50	0.00	0.00	46.00	0.30	0.00	0.00

Emission distribution for the pollutant number 1 (%)
Greenfield
Cement Dust

6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.61	0.00
4	0.00	0.00	8.60	0.17	0.00	55.04	10.32	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.93	0.00	0.00	0.86
2	0.00	0.34	1.20	0.00	18.92	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Total emission of the pollutant number 1 (Ktons/year) = 5.814

Sources distribution for the pollutant number 1
Greenfield

```
    1  2  3  4  5  6  7  8  9
   ---------------------------
 6
 5                        1
 4        1  1     1  1
 3                 1        1
 2     1  1     1
 1
   ---------------------------
```

Total number of sources pollutant 1 = 10

Emission distribution for the pollutant number 2 (%)
Greenfield
SO2

6	0.00	20.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.28	0.00	0.00	20.55	0.00
4	0.00	0.00	54.24	0.30	0.00	0.00	1.27	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	2.54	0.00	0.00	0.08
2	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Total emission of the pollutant number 2 (Ktons/year) = 47.200

Sources distribution for the pollutant number 2
Greenfield

```
    1  2  3  4  5  6  7  8  9
   ---------------------------
 6     1
 5              1        1
 4        1  1        1
 3                 1        1
 2        1
 1
   ---------------------------
```

Total number of sources pollutant 2 = 9

Emission distribution for the pollutant number 3 (%)
Greenfield
NOx

6	0.00	70.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.33	0.00	0.00	8.81	0.00
4	0.00	0.00	18.76	0.16	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	1.63	0.00	0.00	0.00
2	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Total emission of the pollutant number 3 (Ktons/year) = 6.130

Sources distribution for the pollutant number 3
Greenfield

```
     1  2  3  4  5  6  7  8  9
   ---------------------------
 6      1
 5                1        1
 4        1  1
 3                   1
 2        1
 1
   ---------------------------
```

Total number of sources pollutant 3 = 7

Emission distribution for the pollutant number 4 (%)
Greenfield
NH3

6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Total emission of the pollutant number 4 (Ktons/year) = 1.503

Sources distribution for the pollutant number 4
Greenfield

```
     1  2  3  4  5  6  7  8  9
   ---------------------------
 6
 5
 4
 3
 2      1
 1
   ---------------------------
```

Total number of sources pollutant 4 = 1

Emission distribution for the pollutant number 5 (%)
Greenfield
HF

6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	3.51	0.00	0.00	96.49	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Total emission of the pollutant number 5 (Ktons/year) = 0.228

Sources distribution for the pollutant number 5
Greenfield

```
     1  2  3  4  5  6  7  8  9
   ---------------------------
 6
 5
 4
 3
 2      1        1
 1
   ---------------------------
```

Total number of sources pollutant 5 = 2

Emission distribution for the pollutant number 6 (%)
Greenfield
CO

6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	88.93	0.13	0.00	0.00	9.33	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53
2	0.00	0.00	1.07	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Total emission of the pollutant number 6 (Ktons/year) = 1.500

Sources distribution for the pollutant number 6
Greenfield

```
     1  2  3  4  5  6  7  8  9
   ---------------------------
 6
 5
 4        1  1        1
 3                          1
 2        1
 1
   ---------------------------
```

Total number of sources pollutant 6 = 5

Economic damage structure in the city
Greenfield
Listing 1

Source number	Total economical damage components, Thous.$/yr							Economical Damage Totals Thous.$/yr	Economical Damage Totals %
	TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6		
1	2	3	4	5	6	7	8	9	10
1.	1875.7	331.0	37.0	0.0	0.0	1.0	0.0	2244.78	10.01
2.	883.0	218.6	30.3	0.0	0.0	0.0	0.0	1131.90	5.05
3.	203.6	21.7	4.5	0.0	0.0	0.0	0.0	229.83	1.02
4.	0.0	8.5	3.2	0.0	0.0	0.0	0.0	11.70	0.05
5.	147.8	2.5	0.7	0.0	0.0	0.0	0.0	151.00	0.67
6.	191.4	2.2	0.0	0.0	0.0	0.0	0.0	193.61	0.86
7.	907.2	16.6	0.0	0.0	0.0	0.2	0.0	924.08	4.12
8.	46.9	8.2	1.5	0.0	0.0	0.0	0.0	56.65	0.25
9.	0.0	292.8	323.4	0.0	0.0	0.0	0.0	616.19	2.75
10.	976.8	0.0	0.0	0.0	961.8	0.0	0.0	1938.61	8.64
11.	14860.8	0.0	0.0	0.0	0.0	0.0	0.0	14860.80	66.24
12.	43.4	0.0	0.0	15.4	17.5	0.0	0.0	76.31	0.34
Total	20136.5	902.2	400.6	15.4	979.3	1.3	0.0	22435.46	
%	89.8	4.0	1.8	0.1	4.4	0.0	0.0		100.00

Ecomomic damage distribution in the city (%)
Greenfield Pollutant 1
Cement Dust

1% of the economic damage = 201.365 Thous.$/yr

6	0.22	0.25	0.31	0.33	0.34	0.37	0.42	0.23	0.33
5	0.25	0.18	0.09	0.28	14.17	23.68	0.44	0.33	0.37
4	0.25	0.14	0.05	0.36	14.23	23.29	4.90	0.44	0.47
3	0.24	0.31	0.46	0.85	2.10	0.31	0.32	0.48	0.80
2	0.22	0.33	0.54	0.82	2.58	0.29	0.28	0.26	0.27
1	0.19	0.20	0.22	0.21	0.20	0.20	0.20	0.20	0.16
	1	2	3	4	5	6	7	8	9

Ecomomic damage distribution in the city (%)
Greenfield Pollutant 2
SO2

1% of the economic damage = 9.022 Thous.$/yr

[redacted]	4.31	3.74	5.18	3.78	2.72	1.88	1.69	0.92	1.33
[redacted]	3.85	4.45	3.91	3.27	2.32	1.90	1.73	1.12	1.44
4	2.34	2.66	2.11	1.96	1.76	1.77	3.64	1.73	1.66
3	0.84	0.74	0.55	1.22	1.60	1.59	1.62	1.65	1.67
2	0.87	0.86	0.92	1.00	1.37	1.47	1.47	1.44	1.35
1	0.81	0.85	0.87	0.87	0.84	0.94	1.11	1.25	1.04
	1	2	3	4	5	6	7	8	9

Ecomomic damage distribution in the city (%)
Greenfield Pollutant 3
NOx

1% of the economic damage = 4.006 Thous.$/yr

6	8.79	7.49	10.03	6.02	2.54	0.60	0.49	0.25	0.39
5	7.75	10.12	8.60	5.48	1.46	0.60	0.50	0.32	0.42
4	4.09	5.97	4.81	1.83	0.53	0.51	0.53	0.51	0.48
3	0.22	0.42	0.18	0.37	0.46	0.45	0.47	0.47	0.44
2	0.23	0.23	0.27	0.28	0.39	0.42	0.43	0.42	0.39
1	0.21	0.22	0.23	0.23	0.22	0.26	0.31	0.36	0.30
	1	2	3	4	5	6	7	8	9

Ecomomic damage distribution in the city (%)
Greenfield Pollutant 4
NH3

1% of the economic damage = 0.154 Thous.$/yr

6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	13.64	14.88	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	32.57	38.91	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Ecomomic damage distribution in the city (%)
Greenfield Pollutant 5
HF

1% of the economic damage = 9.793 Thous.$/yr

6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.24	0.27	5.15	29.20	0.00	0.00	0.00	0.00
2	0.00	0.58	0.70	6.76	57.10	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9

Ecomomic damage distribution in the city (%)
Greenfield Pollutant 6
CO

1% of the economic damage = 0.013 Thous.$/yr

6	1.79	1.68	1.59	1.72	1.79	1.68	1.53	1.38	1.23
5	1.68	0.85	0.15	0.94	1.78	1.75	1.59	1.42	1.26
4	1.59	0.55	0.06	1.02	1.79	1.76	19.14	1.50	1.49
3	1.72	1.32	1.48	1.77	1.80	1.73	1.58	1.72	2.56
2	1.79	1.80	2.28	2.10	1.78	1.66	1.51	1.38	1.31
1	1.68	1.75	1.78	1.73	1.66	1.55	1.43	1.29	1.16
	1	2	3	4	5	6	7	8	9

Total ecomomic damage distribution in the city (%)
1% of the economic damage = 224.355 Thous.$/yr
Greenfield

6	0.53	0.51	0.67	0.56	0.46	0.42	0.46	0.25	0.36
5	0.52	0.52	0.40	0.48	12.84	21.34	0.47	0.34	0.40
4	0.40	0.34	0.22	0.43	12.86	20.98	4.56	0.47	0.50
3	0.26	0.34	0.46	1.05	3.23	0.35	0.36	0.51	0.79
2	0.24	0.39	0.58	1.08	4.87	0.32	0.31	0.30	0.30
1	0.20	0.22	0.24	0.23	0.22	0.22	0.23	0.24	0.19
	1	2	3	4	5	6	7	8	9

```
Greenfield
In city grid are   6 lines and  9 columns

Calculations are taken for  6 pollutants
Numbers or pollutants used in calculations    1    2    3    4    5    6
Dangerous wind speeds (m/s):                0.5  0.8  1.5  0.8  0.5  0.5
1-st direction - wind from the West to the East,
Step 10  deg. going clockwise
Relief dispersion coefficient =    200.

Map of maximal normalized concentrations
Greenfield              pollutant  1
Cement Dust

Pollution index =   21.59   Number of rasters =   1

   6    0.00  0.00  0.08  0.13  0.27  0.49  0.33  0.16  0.09
   5    0.00  0.05  0.08  0.17  0.50 21.59  0.76  0.33  0.10
   4    0.00  0.00  0.08  0.15  0.34  0.78  0.42  0.19  0.13
   3    0.00  0.06  0.67  0.64  0.20  0.21  0.17  0.11  0.19
   2    0.00  0.00  0.11  0.10  0.17  0.10  0.09  0.07  0.05
   1    0.00  0.00  0.00  0.00  0.05  0.06  0.05  0.09  0.00
          1     2     3     4     5     6     7     8     9


Table of numbers of dangerous wind directions pollutant   1
     1  2  3  4  5  6  7  8  9
   ---------------------------
 6
 5                14
 4
 3
 2
 1
   ---------------------------


Map of maximal normalized concentrations
Greenfield              pollutant  2
SO2

Pollution index =   14.21   Number of rasters =  10

   6    1.34  1.83  1.77  1.22  1.22  1.33  0.45  0.35  0.30
   5    1.01  1.40  1.40  1.01  0.62  0.43  0.43  0.52  0.31
   4    0.67  0.85  0.85  1.06  1.65  0.49  0.35  0.28  0.28
   3    0.44  0.52  0.52  0.76  0.50  0.44  0.33  0.26  0.43
   2    0.31  0.40  0.39  0.57  0.36  0.33  0.29  0.32  0.38
   1    0.31  0.35  0.35  0.37  0.36  0.32  0.23  0.33  0.40
          1     2     3     4     5     6     7     8     9


Table of numbers of dangerous wind directions pollutant   2
     1  2  3  4  5  6  7  8  9
   ---------------------------
 6  20 21 35 36 18  2
 5     26 30
 4           22 33
 3
 2
 1
   ---------------------------
```

Map of maximal normalized concentrations
Greenfield pollutant 3
NOx

Pollution index = 67.38 Number of rasters = 30

6	3.66	4.57	4.67	3.57	2.23	1.90	1.07	0.80	0.67
5	3.08	4.05	4.05	3.08	1.90	1.36	1.00	0.81	0.67
4	2.03	2.60	2.60	2.03	2.31	1.25	0.99	0.79	0.69
3	1.38	1.69	1.73	1.59	1.43	1.22	0.96	0.74	0.69
2	1.03	1.20	1.24	1.50	1.23	1.04	0.89	0.81	0.75
1	0.91	1.01	1.07	1.03	1.00	0.87	0.78	0.71	0.66
	1	2	3	4	5	6	7	8	9

Table of numbers of dangerous wind directions pollutant 3

	1	2	3	4	5	6	7	8	9
6	20	21	35	36	1	1	1		
5	23	26	30	33	35	35			
4	25	27	29	31	33	34			
3	25	27	29	31	32	33			
2		27	28	30	31				
1			28						

Map of maximal normalized concentrations
Greenfield pollutant 4
NH3

Pollution index = 46.94 Number of rasters = 12

6	0.40	0.45	0.49	0.45	0.38	0.31	0.26	0.21	0.18
5	0.57	0.76	0.86	0.70	0.53	0.38	0.30	0.23	0.20
4	0.83	1.62	2.39	1.48	0.77	0.47	0.33	0.25	0.21
3	1.15	4.18	18.81	2.99	0.98	0.51	0.35	0.26	0.21
2	1.04	2.93	6.53	2.33	0.91	0.51	0.35	0.26	0.21
1	0.71	1.13	1.39	1.04	0.66	0.44	0.32	0.25	0.20
	1	2	3	4	5	6	7	8	9

Table of numbers of dangerous wind directions pollutant 4

	1	2	3	4	5	6	7	8	9
6									
5									
4		14	10	6					
3	18	17	8	2					
2		23	29	34					
1		25	28						

Map of maximal normalized concentrations
Greenfield pollutant 5
HF

Pollution index = 19.17 Number of rasters = 8

6	0.25	0.29	0.34	0.40	0.42	0.42	0.38	0.33	0.28
5	0.28	0.34	0.43	0.56	0.64	0.61	0.50	0.40	0.32
4	0.31	0.42	0.56	0.83	1.23	1.10	0.71	0.48	0.36
3	0.38	0.64	0.94	1.24	6.69	2.77	0.94	0.54	0.38
2	0.37	0.50	0.62	1.13	2.98	2.01	0.88	0.53	0.38
1	0.30	0.40	0.51	0.73	0.96	0.88	0.63	0.46	0.34
	1	2	3	4	5	6	7	8	9

Table of numbers of dangerous wind directions pollutant 5

	1	2	3	4	5	6	7	8	9
6									
5									
4					11	7			
3				18	14	4			
2				22	25	33			
1									

Greenfield

Initial measures database for emission decrease in the sources ("+"increase, "-"decrease)

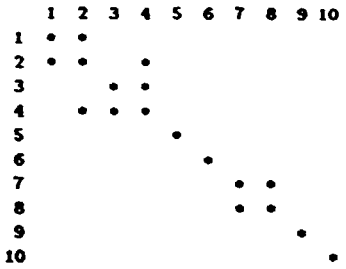
group 1

Meas. number	Capital costs Thous.$	Annual costs Thous.$/year	Pollutants emission variations, %							Economic damage variation %
			TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	2	3	4	5	6	7	8	9	10	11
1.	700.0	157.0	-8.600	-54.24	-4.69	0.00	0.00	-89.60	0.00	-9.91
2.	158.6	38.5	-6.880	0.00	0.00	0.00	0.00	0.00	0.00	-8.27
3.	70.8	8.5	0.000	0.00	-4.22	0.00	0.00	0.00	0.00	-0.08
4.	4940.0	63.5	0.000	0.00	-11.26	0.00	0.00	0.00	0.00	-0.14
5.	95.2	27.5	0.000	0.00	-2.64	0.00	0.00	0.00	0.00	-0.05
6.	87.5	23.3	0.000	0.00	-4.40	0.00	0.00	0.00	0.00	-0.07
7.	330.0	62.0	-0.929	-2.54	-0.41	0.00	0.00	0.00	0.00	-1.01
8.	174.4	35.4	-0.743	0.00	0.00	0.00	0.00	0.00	0.00	-0.89
9.	77.8	5.5	0.000	0.00	-0.49	0.00	0.00	0.00	0.00	-0.01
10.	71.5	1.2	0.000	0.00	-0.82	0.00	0.00	0.00	0.00	-0.01

group 1

Meas. number	Index variation, %							Total index variation %
	TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	12	13	14	15	16	17	18	19
1.	0.00	0.00	-0.27	0.00	0.00	0.00	0.00	-0.18
2.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.	0.00	0.00	-0.25	0.00	0.00	0.00	0.00	-0.17
4.	0.00	0.00	-3.68	0.00	0.00	0.00	0.00	-2.48
5.	0.00	0.00	-0.03	0.00	0.00	0.00	0.00	-0.02
6.	0.00	0.00	-0.11	0.00	0.00	0.00	0.00	-0.07
7.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The table of the incompatible measures
group 1



Greenfield
Initial measures database for emission decrease in the sources ("+"increase, "-"decrease)

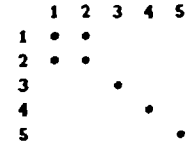
group 2

Meas. number	Capital costs Thous.$	Annual costs Thous.$/year	Pollutants emission variations, %							Economic damage variation %
			TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	2	3	4	5	6	7	8	9	10	11
1.	16.8	9.1	0.000	-0.28	-0.23	0.00	0.00	0.00	0.00	-0.05
2.	10.0	1.6	0.000	-0.04	-0.33	0.00	0.00	0.00	0.00	-1.01
3.	6.0	0.4	-1.185	0.15	0.33	0.00	0.00	-1.07	0.00	-0.99
4.	6.0	0.4	-0.843	0.06	0.00	0.00	0.00	-0.53	0.00	-1.00
5.	9.0	0.6	-1.011	0.08	0.00	0.00	0.00	-0.93	0.00	-0.99

group 2

Meas. number	Index variation, %							Total index variation %
	TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	12	13	14	15	16	17	18	19
1.	0.00	-7.58	-0.37	0.00	0.00	0.00	0.00	-1.32
2.	0.00	-7.58	-0.52	0.00	0.00	0.00	0.00	-1.43
3.	0.00	0.00	-0.16	0.00	0.00	0.00	0.00	-0.11
4.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The table of the incompatible measures
group 2



Greenfield
Initial measures database for emission decrease in the sources ("+"increase, "-"decrease)

group 3

Meas. number	Capital costs Thous.$	Annual costs Thous.$/year	Pollutants emission variations, %							Economic damage variation %
			TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	2	3	4	5	6	7	8	9	10	11
1.	7840.0	165.0	0.000	-20.55	-70.15	0.00	0.00	0.00	0.00	-2.70
2.	650.0	99.0	-18.804	0.00	0.00	0.00	-96.49	0.00	0.00	-8.40
3.	60.4	17.0	-53.994	0.00	0.00	0.00	0.00	0.00	0.00	-69.15
4.	1260.0	78.0	0.000	0.00	0.00	-94.70	-1.43	0.00	0.00	-0.09

group 3

Meas. number	Index variation, %							Total index variation %
	TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	12	13	14	15	16	17	18	19
1.	0.00	-62.54	-70.02	0.00	0.00	0.00	0.00	-56.06
2.	0.00	0.00	0.00	0.00	-60.56	0.00	0.00	-11.61
3.	-80.13	0.00	0.00	0.00	0.00	0.00	0.00	-17.30
4.	0.00	0.00	0.00	-76.82	0.00	0.00	0.00	-36.06

The table of the incompatible measures
group 3

	1	2	3	4
1	•			
2		•		
3			•	
4				•

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 1

Criterion Number		8
Investment	($ million)	9.28
Emission	variation (%)	
Cement Dust		-84.44
SO2		-74.53
NOx		-74.84
NH3		0.00
HF		-96.49
CO		-92.13
Economic Damage	variation (%)	-94.16
Concentration	variation (%)	
Cement Dust		-80.13
SO2		-70.12
NOx		-70.98
NH3		0.00
HF		-60.56
CO		0.00
Total Index	variation (%)	-51.21

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 2

Criterion Number		16
Investment	($ million)	14.76
Emission	variation (%)	
Cement Dust		-72.80
SO2		-20.59
NOx		-81.73
NH3		-94.70
HF		-97.92
CO		0.00
Economic Damage	variation (%)	-81.51
Concentration	variation (%)	
Cement Dust		-80.13
SO2		-70.12
NOx		-74.23
NH3		-76.82
HF		-60.56
CO		0.00
Total Index	variation (%)	-73.81

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 3

Criterion Number		16
Investment	($ million)	1.98
Emission	variation (%)	
Cement Dust		-72.80
SO2		-0.04
NOx		-0.33
NH3		-94.70
HF		-97.92
CO		0.00
Economic Damage	variation (%)	-78.66
Concentration	variation (%)	
Cement Dust		-80.13
SO2		-7.58
NOx		-0.52
NH3		-76.82
HF		-60.56
CO		0.00
Total Index	variation (%)	-39.22

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 4

Criterion Number		16
Investment	($ million)	9.82
Emission	variation (%)	
Cement Dust		-72.80
SO2		-20.59
NOx		-70.47
NH3		-94.70
HF		-97.92
CO		0.00
Economic Damage	variation (%)	-81.36
Concentration	variation (%)	
Cement Dust		-80.13
SO2		-70.12
NOx		-70.55
NH3		-76.82
HF		-60.56
CO		0.00
Total Index	variation (%)	-72.34

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 5

Criterion Number		3
Investment	($ million)	13.74
Emission	variation (%)	
Cement Dust		-8.60
SO2		-74.83
NOx		-94.28
NH3		0.00
HF		0.00
CO		-89.60
Economic Damage	variation (%)	-13.90
Concentration	variation (%)	
Cement Dust		0.00
SO2		-70.12
NOx		-74.64
NH3		0.00
HF		0.00
CO		0.00
Total Index	variation (%)	-35.59

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 6

Criterion Number		8
Investment	($ million)	1.44
Emission	variation (%)	
Cement Dust		-84.44
SO2		-53.98
NOx		-4.69
NH3		0.00
HF		-96.49
CO		-92.13
Economic Damage	variation (%)	-91.46
Concentration	variation (%)	
Cement Dust		-80.13
SO2		-7.58
NOx		-0.95
NH3		0.00
HF		-60.56
CO		0.00
Total Index	variation (%)	-18.09

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 7

Criterion Number		11
Investment	($ million)	0.79
Emission	variation (%)	
Cement Dust		-9.79
SO2		-54.13
NOx		-8.91
NH3		0.00
HF		0.00
CO		-90.67
Economic Damage	variation (%)	-11.99
Concentration	variation (%)	
Cement Dust		0.00
SO2		-7.58
NOx		-1.20
NH3		0.00
HF		0.00
CO		0.00
Total Index	variation (%)	-1.11

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 8

Criterion Number		11
Investment	($ million)	8.63
Emission	variation (%)	
Cement Dust		-9.79
SO2		-74.68
NOx		-79.06
NH3		0.00
HF		0.00
CO		-90.67
Economic Damage	variation (%)	-14.70
Concentration	variation (%)	
Cement Dust		0.00
SO2		-70.12
NOx		-71.22
NH3		0.00
HF		0.00
CO		0.00
Total Index	variation (%)	-34.23

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 9

Criterion Number		16
Investment	($ million)	6.92
Emission	variation (%)	
Cement Dust		-72.80
SO2		-0.04
NOx		-11.58
NH3		-94.70
HF		-97.92
CO		0.00
Economic Damage	variation (%)	-78.80
Concentration	variation (%)	
Cement Dust		-80.13
SO2		-7.58
NOx		-4.21
NH3		-76.82
HF		-60.56
CO		0.00
Total Index	variation (%)	-40.69

Optimal strategy ("+"increase, "-"decrease)

Criterion number 8 Value of capital costs 9.30 $ million

Group number	Meas. number	Capital costs ($ mlln.)	Annual costs ($ mln./year)	Pollutant emission variations, %							Economic damage variation %
				TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	2	3	4	5	6	7	8	9	10	11	12
3.	3.	0.06	0.017	-53.99	0.00	0.00	0.00	0.00	0.00	0.00	-69.15
2.	4.	0.01	0.000	-0.84	0.06	0.00	0.00	0.00	-0.53	0.00	-1.00
2.	3.	0.01	0.000	-1.19	0.15	0.33	0.00	0.00	-1.07	0.00	-0.99
2.	5.	0.01	0.001	-1.01	0.08	0.00	0.00	0.00	-0.93	0.00	-0.99
2.	2.	0.01	0.002	0.00	-0.04	-0.33	0.00	0.00	0.00	0.00	-1.01
1.	1.	0.70	0.157	-8.60	-54.24	-4.69	0.00	0.00	-89.60	0.00	-9.91
3.	2.	0.65	0.099	-18.80	0.00	0.00	0.00	-96.49	0.00	0.00	-8.40
3.	1.	7.84	0.165	0.00	-20.55	-70.15	0.00	0.00	0.00	0.00	-2.70
Total		9.3	0.4	-84.44	-74.53	-74.84	0.00	-96.49	-92.13	0.00	-94.16

Group number	Meas. number	Index variations, %							Total index variation %
		TSP	GAS 1	GAS 2	GAS 3	GAS 4	GAS 5	GAS 6	
1	2	14	15	16	17	18	19	20	21
3.	3.	-80.13	0.00	0.00	0.00	0.00	0.00	0.00	-10.22
2.	4.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.	3.	0.00	0.00	-0.16	0.00	0.00	0.00	0.00	-0.06
2.	5.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.	2.	0.00	-7.58	-0.52	0.00	0.00	0.00	0.00	-0.85
1.	1.	0.00	0.00	-0.27	0.00	0.00	0.00	0.00	-0.11
3.	2.	0.00	0.00	0.00	0.00	-60.56	0.00	0.00	-6.86
3.	1.	0.00	-62.54	-70.02	0.00	0.00	0.00	0.00	-33.12
Total		-80.13	-70.12	-70.98	0.00	-60.56	0.00	0.00	-51.21

3.2 Data about a Region

Dirty Smokes Valley

TOTAL number of sources: 11

Mean annual precipitation (mm/yr): 600.0
Mean annual wet period duration : 0.12
Mean annual surface wind speed (m/s): 5.1

8-point surface wind rose :	South	S-West	West	N-West	Nord	N-East	East	S-East
Mean annual recurrence :	0.400	0.100	0.100	0.050	0.050	0.050	0.050	0.200

Mean annual mixing layer height (m): 750.0

12-point mixing layer wind rose :	Dir.1	Dir.2	Dir.3	Dir.4	Dir.5	Dir.6	Dir.7	Dir.8	Dir.9	Dir.10	Dir.11	Dir.12
Mean annual recurrence :	0.200	0.200	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.100	0.100

Mean annual surface air temperature (C): 5.0

Regular grid parameters for the city :
The quantity of cells from the West to the East (X-axes): 12
The quantity of cells from the South to the Nord(Y-axes): 9
Grid step (km): 10.0
Accuracy of the "SIGMA" calculation: 3

Pollutant numbers upon which the data has been entered: 1 2 3 4 5

Pollutant	Agressiveness
1. Cement Dust	45.0
2. Sulfur Dioxide	22.0
3. Nitrogen Oxides	41.1
4. Ammonium	4.6
5. Carbon Dioxide	1.0

"SIGMA matrix"
Dirty Smokes Valley

9	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
8	0.90	0.90	4.60	4.60	2.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90
7	0.90	0.90	3.80	3.80	1.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
6	0.90	0.90	1.10	1.20	1.30	1.80	1.30	0.90	0.90	0.90	0.90	0.90
5	0.90	1.60	2.00	2.10	2.40	3.10	3.10	3.30	2.60	1.10	0.90	0.90
4	0.90	0.90	1.60	3.90	7.20	8.30	6.90	6.40	3.70	2.40	1.80	1.80
3	0.90	0.90	2.40	3.40	8.10	7.80	4.90	1.70	1.50	1.70	4.20	4.00
2	0.90	0.90	1.10	0.90	1.90	2.10	2.40	1.80	1.50	1.80	3.50	2.30
1	0.90	1.40	0.90	0.90	0.90	0.90	0.90	0.90	0.90	1.50	2.20	2.00
	1	2	3	4	5	6	7	8	9	10	11	12

Information about the sources
Dirty Smokes Valley
Listing 1

Source number	Heig. m	Diam. m	Emiss. temp. C	Emiss. rate m/s	Coef. SIGMA for sour.	% TSP sep.	Total emission of pollutants, Ktons/year TSP	SO2	NOx	GAS 3	GAS 4	GAS 5	GAS 6	Source Coordinates,km X	Y
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1.	150.0	4.0	220.0	97.0	1.31	50.0	1.400	18.000	8.000	0.000	6.000	0.000	0.000	17.40	52.70
2.	150.0	3.0	230.0	160.0	2.39	91.0	3.000	20.000	10.000	0.000	9.000	0.000	0.000	28.30	42.40
3.	250.0	4.0	200.0	300.0	1.25	92.0	14.000	55.000	16.000	0.000	25.000	0.000	0.000	18.20	14.90
4.	100.0	3.0	200.0	103.0	1.45	94.0	2.900	12.000	8.000	0.000	9.000	0.000	0.000	64.80	47.10
5.	100.0	1.8	150.0	47.0	3.63	95.0	2.000	12.000	5.000	0.000	7.000	0.000	0.000	43.50	34.70
6.	50.0	0.4	50.0	7.0	2.40	80.0	1.900	0.000	0.000	1.000	14.000	0.000	0.000	42.00	41.80
7.	100.0	30.0	90.0	4.6	5.96	90.0	0.000	0.000	0.000	10.000	10.000	0.000	0.000	53.00	34.00
8.	200.0	5.0	200.0	140.0	3.69	95.0	5.800	32.000	15.000	0.000	10.000	0.000	0.000	74.00	14.00
9.	100.0	4.0	150.0	80.0	1.27	8.0	8.000	12.000	7.000	0.000	10.000	0.000	0.000	107.00	34.00
10.	100.0	5.0	100.0	95.0	2.20	95.0	7.000	12.000	9.000	0.000	10.000	0.000	0.000	105.00	27.00
11.	250.0	8.0	200.0	180.0	2.54	97.0	14.000	27.000	20.000	0.000	20.000	0.000	0.000	36.10	43.00
Total emission of pollutants in region							60.0	200.0	100.0	11.0	130.0	0.0	0.0		

Emission distribution for the pollutant number 1 (%)
Dirty Smokes Valley

Cement Dust

9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	2.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	5.00	23.33	3.17	0.00	4.83	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	3.33	0.00	0.00	0.00	0.00	0.00	13.33	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.67	0.00
2	0.00	23.33	0.00	0.00	0.00	0.00	0.00	9.67	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

Total emission of the pollutant number 1 (Ktons/year) = 60.000

Sources distribution for the pollutant number 1
Dirty Smokes Valley

```
     1  2  3  4  5  6  7  8  9 10 11 12
    ------------------------------------
 9
 8
 7
 6      1
 5         1  1  1     1
 4               1                 1
 3                                 1
 2      1                 1
 1
    ------------------------------------
```

Total number of sources pollutant 1 = 10

Emission distribution for the pollutant number 2 (%)
Dirty Smokes Valley

Sulfur Dioxide

9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	10.00	13.50	0.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00
2	0.00	27.50	0.00	0.00	0.00	0.00	0.00	16.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

Total emission of the pollutant number 2 (Ktons/year) = 200.000

Sources distribution for the pollutant number 2
Dirty Smokes Valley

```
     1  2  3  4  5  6  7  8  9 10 11 12
    ------------------------------------
 9
 8
 7
 6      1
 5         1  1        1
 4               1                 1
 3                                 1
 2      1                 1
 1
    ------------------------------------
```

Total number of sources pollutant 2 = 9

Emission distribution for the pollutant number 3 (%)
Dirty Smokes Valley

Nitrogen Oxides

9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	10.00	20.00	0.00	0.00	8.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	5.00	0.00	0.00	0.00	0.00	0.00	7.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.00	0.00
2	0.00	18.00	0.00	0.00	0.00	0.00	0.00	15.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

Total emission of the pollutant number 3 (Ktons/year) = 100.000

Sources distribution for the pollutant number 3
Dirty Smokes Valley

	1	2	3	4	5	6	7	8	9	10	11	12
9												
8												
7												
6		1										
5			1	1			1					
4					1						1	
3											1	
2		1						1				
1												

Total number of sources pollutant 3 = 9

Emission distribution for the pollutant number 4 (%)
Dirty Smokes Valley

Ammonium

9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	9.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	90.91	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

Total emission of the pollutant number 4 (Ktons/year) = 11.000

Sources distribution for the pollutant number 4
Dirty Smokes Valley

```
     1  2  3  4  5  6  7  8  9 10 11 12
   ------------------------------------
 9
 8
 7
 6
 5              1
 4                 1
 3
 2
 1
   ------------------------------------
```

Total number of sources pollutant 4 = 2

Emission distribution for the pollutant number 5 (%)
Dirty Smokes Valley

Carbon Dioxide

9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	4.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	6.92	15.38	10.77	0.00	6.92	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	5.38	7.69	0.00	0.00	0.00	0.00	7.69	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.69	0.00
2	0.00	19.23	0.00	0.00	0.00	0.00	0.00	7.69	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

Total emission of the pollutant number 5 (Ktons/year) = 130.000

Sources distribution for the pollutant number 5
Dirty Smokes Valley

```
     1  2  3  4  5  6  7  8  9 10 11 12
   ------------------------------------
 9
 8
 7
 6     1
 5        1  1  1     1
 4              1  1              1
 3                                1
 2     1                 1
 1
   ------------------------------------
```

Total number of sources pollutant 5 = 11

Economic damage structure in the region
Dirty Smokes Valley
Listing 1

Source number	Total economical damage components, Thous.$/yr							Economical Damage Totals Thous.$/yr	Economical Damage Totals %
	TSP	SO2	NOx	GAS 3	GAS 4	GAS 5	GAS 6		
1	2	3	4	5	6	7	8	9	10
1.	19.1	119.8	99.5	0.0	1.8	0.0	0.0	240.12	1.35
2.	72.4	236.1	220.5	0.0	4.8	0.0	0.0	533.85	3.01
3.	124.4	238.9	145.1	0.0	4.9	0.0	0.0	514.31	2.90
4.	64.8	131.1	163.3	0.0	4.5	0.0	0.0	363.62	2.05
5.	130.8	383.6	298.6	0.0	10.2	0.0	0.0	823.24	4.64
6.	863.1	0.0	0.0	9.7	29.4	0.0	0.0	902.12	5.09
7.	0.0	0.0	0.0	137.6	29.9	0.0	0.0	167.53	0.94
8.	184.6	498.0	436.1	0.0	7.1	0.0	0.0	1125.81	6.35
9.	10944.0	133.8	145.8	0.0	5.1	0.0	0.0	11228.68	63.29
10.	333.9	279.8	392.1	0.0	10.6	0.0	0.0	1016.33	5.73
11.	251.6	237.2	328.3	0.0	8.0	0.0	0.0	825.03	4.65
Total	12988.6	2258.3	2230.2	147.3	116.2	0.0	0.0	17740.62	
%	73.2	12.7	12.6	0.8	0.7	0.0	0.0		100.00

Ecomomic damage distribution in the region (%)
Dirty Smokes Valley Pollutant 1
Cement Dust

1% of the economic damage = 129.886 Thous.$/yr

9	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.03	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.03	0.11	0.11	0.05	0.00	0.02	0.00	0.00	0.00	0.00	0.00
6	0.00	0.09	0.26	0.34	0.19	0.01	0.24	0.01	0.00	0.00	0.00	0.00
5	0.01	0.03	0.24	0.71	7.29	0.00	0.23	0.02	0.00	0.00	15.80	0.00
4	0.04	0.06	0.06	0.11	0.68	0.00	0.06	0.08	0.01	0.00	69.95	0.00
3	0.04	0.15	0.15	0.00	0.00	0.00	0.13	0.29	0.05	0.00	1.07	0.00
2	0.00	0.18	0.20	0.00	0.00	0.01	0.11	0.57	0.07	0.00	0.00	0.00
1	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

Ecomomic damage distribution in the region (%)
Dirty Smokes Valley Pollutant 2
Sulfur Dioxide

1% of the economic damage = 22.583 Thous.$/yr

9	0.00	0.04	0.03	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.02	0.24	0.33	0.29	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.14	1.10	1.50	0.84	0.30	0.00	0.40	0.00	0.00	0.00	0.00	0.00
6	0.03	2.62	4.01	2.67	1.17	0.17	3.07	0.13	0.00	0.00	0.00	0.00
5	0.23	0.41	3.52	6.07	7.08	0.00	2.36	0.46	0.00	0.00	1.74	0.00
4	0.57	0.80	0.84	0.54	10.83	0.05	1.15	1.55	0.15	0.00	11.71	0.00
3	0.45	1.65	1.61	0.00	0.00	0.00	2.12	4.50	0.75	0.00	4.87	0.00
2	0.00	1.64	1.96	0.00	0.00	0.16	1.66	8.06	1.11	0.00	0.00	0.00
1	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2	3	4	5	6	7	8	9	10	11	12

The table of the incompatible measures
group 1

	1	2	3	4	5	6	7	8	9	10
1	•	•								
2	•	•	•							
3		•	•							
4				•	•					
5				•	•	•				
6					•	•				
7							•	•		
8							•	•	•	
9								•	•	
10										•

TEST REGION
Initial measures database for emission decrease in the sources ("+"increase, "-"decrease)

group 2

Meas. number	Capital costs Thous.$	Annual costs Thous.$/year	Pollutants emission variations, % TSP	SO x	NO x	GAS 3	GAS 4	GAS 5	GAS 6	Economic damage variation %
1	2	3	4	5	6	7	8	9	10	11
1.	100.0	50.0	-1.21	0.00	0.00	0.00	0.00	0.00	0.00	-0.09
2.	160.0	30.0	-4.83	-6.00	0.96	0.00	-0.35	0.00	0.00	-0.99
3.	200.0	10.0	-2.68	0.60	0.80	-9.09	-10.08	0.00	0.00	-4.88
4.	500.0	50.0	-3.17	0.00	2.00	-9.09	-5.38	0.00	0.00	-4.72
5.	200.0	30.0	-1.45	-3.20	-7.50	0.00	-3.85	0.00	0.00	-1.97
6.	100.0	50.0	-0.48	-3.20	-9.00	0.00	-0.77	0.00	0.00	-2.09
7.	300.0	60.0	-0.67	-0.90	-0.25	0.00	-0.81	0.00	0.00	-0.56
8.	500.0	50.0	-1.00	-1.20	0.00	0.00	-1.62	0.00	0.00	-0.67

Number meas.	Variation total deposit. %	Variation Sulphur leaving the region, % Total	sector1	sector2	sector3	sector4	sector5	sector6	sector7	sector8	Variation index danger conifer
1	12	13	14	15	16	17	18	19	20	21	22
1.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.	-6.32	-5.94	-6.27	-6.22	-6.11	-5.57	-5.41	-5.63	-5.66	-5.95	-9.68
3.	0.63	0.59	0.63	0.62	0.61	0.56	0.54	0.56	0.57	0.59	1.04
4.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.	-3.69	-3.11	-3.44	-3.04	-2.94	-2.82	-3.12	-3.35	-3.37	-3.44	-5.70
6.	-3.69	-3.11	-3.44	-3.04	-2.94	-2.82	-3.12	-3.35	-3.37	-3.44	-5.70
7.	-0.98	-0.89	-0.88	-0.90	-0.89	-0.88	-0.86	-0.88	-0.88	-0.87	-1.80
8.	-1.30	-1.18	-1.18	-1.20	-1.18	-1.18	-1.15	-1.17	-1.18	-1.15	-2.39

Number meas.	Variation total deposit. %	Variation Nitrogen leaving the region, %							
		Total	sector1	sector2	sector3	sector4	sector5	sector6	sector7	sector8
1	22	23	24	25	26	27	28	29	30	31
1.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.	1.02	0.95	0.99	0.99	0.98	0.89	0.85	0.89	0.90	0.95
3.	0.85	0.79	0.83	0.83	0.82	0.74	0.71	0.74	0.75	0.79
4.	2.09	1.98	1.94	2.06	2.05	1.99	1.91	1.86	1.87	1.84
5.	-8.89	-7.23	-6.05	-6.89	-6.70	-6.47	-7.39	-8.07	-8.13	-8.25
6.	-10.66	-8.67	-9.66	-8.27	-8.03	-7.76	-8.87	-9.68	-9.75	-9.90
7.	-0.28	-0.24	-0.24	-0.25	-0.25	-0.25	-0.24	-0.25	-0.25	-0.24
8.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The table of the incompatible measures
group 2

	1	2	3	4	5	6	7	8
1	•	•						
2	•	•						
3			•	•				
4			•	•				
5					•	•		
6					•	•		
7							•	
8								•

TEST REGION
Initial measures database for emission decrease in the sources ("+"increase, "-"decrease)

group 3

Meas. number	Capital costs Thous.$	Annual costs Thous.$/year	Pollutants emission variations, %							Economic damage variation %
			TSP	SO x	NO x	GAS 3	GAS 4	GAS 5	GAS 6	
1	2	3	4	5	6	7	8	9	10	11
1.	100.0	70.0	-5.33	0.00	0.00	0.00	0.00	0.00	0.00	-61.07
2.	300.0	30.0	0.00	-2.40	0.00	0.00	0.00	0.00	0.00	-0.30
3.	500.0	100.0	-1.33	-3.00	-2.10	0.00	0.00	0.00	0.00	-6.79
4.	400.0	50.0	-11.67	-6.00	1.80	0.00	-0.77	0.00	0.00	-3.02
5.	200.0	20.0	-3.50	-2.40	-0.90	0.00	-1.54	0.00	0.00	-1.43
6.	300.0	70.0	-7.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.43
7.	500.0	150.0	-4.67	-4.05	-4.00	0.00	-4.62	0.00	0.00	-1.07
8.	900.0	200.0	-7.00	-6.75	-6.00	0.00	-4.62	0.00	0.00	-1.66

Number meas.	Variation total deposit. %	Variation Sulphur leaving the region, %								Variation index danger conifer
		Total	sector1	sector2	sector3	sector4	sector5	sector6	sector7	sector8	
1	12	13	14	15	16	17	18	19	20	21	22
1.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.	-2.26	-2.42	-2.88	-2.57	-2.36	-2.01	-2.07	-2.34	-2.41	-2.74	-3.05
3.	-2.83	-3.03	-3.60	-3.21	-2.95	-2.52	-2.58	-2.93	-3.02	-3.42	-3.78
4.	-5.78	-6.04	-7.21	-6.38	-5.70	-4.93	-5.41	-6.06	-6.15	-6.85	-7.33
5.	-2.31	-2.42	-2.88	-2.55	-2.28	-1.97	-2.16	-2.42	-2.46	-2.74	-3.10
6.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.	-4.05	-4.05	-3.96	-4.20	-4.13	-4.14	-4.02	-3.81	-3.82	-3.73	-8.15
8.	-6.75	-6.75	-6.61	-6.99	-6.89	-6.90	-6.71	-6.36	-6.37	-6.21	-13.35

Number meas.	Variation total deposit. %	Variation Nitrogen leaving the region, %								
		Total	sector1	sector2	sector3	sector4	sector5	sector6	sector7	sector8
1	22	23	24	25	26	27	28	29	30	31
1.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.	-1.95	-2.13	-2.62	-2.27	-2.06	-1.69	-1.75	-2.06	-2.14	-2.50
4.	1.72	1.82	2.24	1.92	1.68	1.41	1.60	1.85	1.88	2.14
5.	-0.86	-0.91	-1.12	-0.96	-0.84	-0.70	-0.80	-0.92	-0.94	-1.07
6.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.	-4.00	-4.00	-3.79	-4.13	-4.12	-4.20	-4.04	-3.74	-3.75	-3.58
8.	-6.00	-6.00	-5.68	-6.19	-6.17	-6.30	-6.05	-5.61	-5.62	-5.36

The table of the incompatible measures
group 3

	1	2	3	4	5	6	7	8
1	•							
2		•						
3			•					
4				•	•			
5				•	•			
6						•		
7							•	
8								•

ESULTS OF MULTICRITERIA OPTIMIZATION

RAMETERS OF MEASURE SET 1

riterion Number		2
vestment	($ million)	1.55
ission	variation (%)	
Cement Dust		-10.87
Sulfur Dioxide		-33.20
Nitrogen Oxides		-10.80
Ammonium		0.00
Carbon Dioxide		-6.62
onomic Damage	variation (%)	-3.41
lfur Deposition	variation (%)	
lfur Deposition	variation (%)	-31.19
lfur Export	variation (%)	-33.56
rest Damage	variation (%)	-61.14
troger Deposition	variation (%)	-9.93
trog[redacted]xport	variation (%)	-10.98

ULTS OF MULTICRITERIA OPTIMIZATION

AMETERS OF MEASURE SET 2

terion Number		2
estment	($ million)	1.60
ssion	variation (%)	
Cement Dust		-11.33
Sulfur Dioxide		-35.00
Nitrogen Oxides		-7.60
Ammonium		0.00
Carbon Dioxide		-5.23
nomic Damage	variation (%)	-3.34
fur Deposition	variation (%)	
fur Deposition	variation (%)	-32.64
fur [redacted]port	variation (%)	-35.42
st Damage	variation (%)	-63.37
ogen Deposition	variation (%)	-7.49
ogen Export	variation (%)	-7.62

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 3

Criterion Number		2
Investment	($ million)	1.85
Emission	variation (%)	
Cement Dust		-13.87
Sulfur Dioxide		-39.20
Nitrogen Oxides		-6.30
Ammonium		0.00
Carbon Dioxide		-5.58
Economic Damage	variation (%)	-3.89
Sulfur Deposition	variation (%)	
Sulfur Deposition	variation (%)	-36.91
Sulfur Export	variation (%)	-39.61
Forest Damage	variation (%)	-72.18
Nitrogen Deposition	variation (%)	-5.69
[illegible]ogen Export	variation (%)	-6.42

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 4

Criterion Number		2
Investment	($ million)	1.90
Emission	variation (%)	
Cement Dust		-14.33
Sulfur Dioxide		-41.00
Nitrogen Oxides		-3.10
Ammonium		0.00
Carbon Dioxide		-4.19
Economic Damage	variation (%)	-3.82
Sulfur Deposition	variation (%)	
Sulfur Deposition	variation (%)	-38.36
S[illegible]r Export	variation (%)	-41.47
Forest Damage	variation (%)	-74.41
Nitrogen Deposition	variation (%)	-3.25
Nitrogen Export	variation (%)	-3.07

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 5

Criterion Number		3
Investment	($ million)	1.60
Emission	variation (%)	
Cement Dust		-15.17
Sulfur Dioxide		-13.20
Nitrogen Oxides		-10.90
Ammonium		0.00
Carbon Dioxide		-10.77
Economic Damage	variation (%)	-4.16
Sulfur Deposition	variation (%)	
Sulfur Deposition	variation (%)	-13.12
Sulfur Export	variation (%)	-13.21
Forest Damage	variation (%)	-24.60
Nitrogen Deposition	variation (%)	-10.85
Nitrogen Export	variation (%)	-10.90

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 6

Criterion Number		5
Investment	($ million)	1.06
Emission	variation (%)	
Cement Dust		-9.97
Sulfur Dioxide		-9.80
Nitrogen Oxides		-5.74
Ammonium		-9.09
Carbon Dioxide		-15.88
Economic Damage	variation (%)	-8.51
Sulfur Deposition	variation (%)	
Sulfur Deposition	variation (%)	-10.69
Sulfur Export	variation (%)	-9.64
Forest Damage	variation (%)	-16.73
Nitrogen Deposition	variation (%)	-7.01
Nitrogen Export	variation (%)	-5.49

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 7

Criterion Number		3
Investment	($ million)	2.15
Emission	variation (%)	
Cement Dust		-10.87
Sulfur Dioxide		-19.45
Nitrogen Oxides		-16.20
Ammonium		0.00
Carbon Dioxide		-8.54
Economic Damage	variation (%)	-2.99
Sulfur Deposition	variation (%)	
Sulfur Deposition	variation (%)	-17.70
Sulfur Export	variation (%)	-19.76
Forest Damage	variation (%)	-35.39
Nitrogen Deposition	variation (%)	-15.21
Nitrogen Export	variation (%)	-16.40

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 8

Criterion Number		5
Investment	($ million)	0.86
Emission	variation (%)	
Cement Dust		-9.63
Sulfur Dioxide		-9.50
Nitrogen Oxides		-5.99
Ammonium		-9.09
Carbon Dioxide		-15.08
Economic Damage	variation (%)	-8.41
Sulfur Deposition	variation (%)	
Sulfur Deposition	variation (%)	-10.36
Sulfur Export	variation (%)	-9.35
Forest Damage	variation (%)	-16.13
Nitrogen Deposition	variation (%)	-7.29
Nitrogen Export	variation (%)	-5.73

RESULTS OF MULTICRITERIA OPTIMIZATION

PARAMETERS OF MEASURE SET 9

Criterion Number 5
Investment ($ million) 1.20

Emission variation (%)
Cement Dust -5.80
Sulfur Dioxide -4.70
Nitrogen Oxides -6.95
Ammonium -9.09
Carbon Dioxide -16.35

Economic Damage variation (%) -8.08

Sulfur Deposition variation (%)
Sulfur Deposition variation (%) -5.34
Sulfur Export variation (%) -4.59

Forest Damage variation (%) -8.85

Nitrogen Deposition variation (%) -8.31
Nitrogen Export variation (%) -6.68

Optimal strategy ("+"increase, "-"decrease)

Criterion number 2 Value of capital costs 1.6 $ Million

Group number	Meas. number	Capital costs $ milln.	Annual costs $ milln./year	Pollutants emission variations, % TSP	SO x	NO x	GAS 3	GAS 4	GAS 5	GAS 6	Economic damage variation %
1	2	3	4	5	6	7	8	9	10	11	12
1.	9.	0.3	0.0	0.00	-13.75	0.00	0.00	0.00	0.00	0.00	-0.67
1.	1.	0.2	0.0	-0.70	-4.50	-1.60	0.00	-0.46	0.00	0.00	-0.48
1.	4.	0.2	0.0	-2.00	-4.00	-3.00	0.00	-1.38	0.00	0.00	-1.07
1.	3.	0.2	0.1	-1.17	-2.70	-0.80	0.00	-0.92	0.00	0.00	-0.31
1.	7.	0.7	0.1	-7.00	-8.25	-5.40	0.00	-3.85	0.00	0.00	-0.87
Total		1.5	0.2	-10.87	-33.20	-10.80	0.00	-6.62	0.00	0.00	-3.41

Group number	Meas. number	Total deposit. variation %	Sulphur leaving the region, % Total	sector1	sector2	sector3	sector4	sector5	sector6	sector7	sector8	Danger conifer index variation
1	2	13	14	15	16	17	18	19	20	21	22	23
1.	9.	-13.49	-13.80	-12.26	-12.85	-13.94	-15.10	-14.67	-14.40	-14.50	-14.06	-25.76
1.	1.	-3.62	-4.66	-4.43	-4.85	-4.84	-4.94	-4.80	-4.38	-4.11	-3.91	-7.10
1.	4.	-3.81	-4.03	-3.85	-4.14	-4.13	-4.23	-4.11	-3.82	-3.78	-3.62	-7.88
1.	3.	-2.17	-2.79	-2.66	-2.91	-2.90	-2.96	-2.88	-2.63	-2.46	-2.34	-4.32
1.	7.	-8.09	-8.28	-7.36	-7.71	-8.37	-9.06	-8.80	-8.64	-8.70	-8.44	-16.08
Total		-31.19	-33.56	-30.57	-32.46	-34.18	-36.29	-35.26	-33.88	-33.54	-32.37	-61.14

Group number	Meas. number	Total deposit. variation %	Variation Nitrogen leaving the region, %							
			Total	sector1	sector2	sector3	sector4	sector5	sector6	sector7	sector8
1	2	22	23	24	25	26	27	28	29	30	31
1.	9.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.	1.	-1.22	-1.68	-1.53	-1.74	-1.77	-1.85	-1.77	-1.56	-1.43	-1.32
1.	4.	-2.83	-3.03	-2.78	-3.10	-3.13	-3.30	-3.17	-2.86	-2.81	-2.62
1.	3.	-0.61	-0.84	-0.77	-0.87	-0.88	-0.92	-0.89	-0.78	-0.72	-0.66
1.	7.	-5.27	-5.43	-4.52	-4.85	-5.51	-6.23	-5.97	-5.81	-5.85	-5.57
Total		-9.93	-10.98	-9.60	-10.56	-11.30	-12.30	-11.80	-11.01	-10.81	-10.18

4 IPAC Mathematical Models and Algorithms

The descriptions presented provide the interested user with a short, general explanation of the mathematical methods and algorithms implemented in the IPAC system.

4.1 Mathematical and Conceptual Background

The set Φ of all possible emission sources is considered for a given simulation site. Each source $\bar{\varphi} \in \Phi$ impacting the surface atmosphere on-site can be characterized by a vector of parameters

$$\bar{\varphi} = \left\{\varphi^j\right\}_{j=1}^{N} \tag{4.1}$$

The geometrical height of the source, the rate and temperature of emission, its mass as well as the mass of each pollutant, source coordinates, etc. are represented in the vector.

Suppose that on the set Φ there is a set Λ that includes the initial measures transforming these source vectors (separation of gases, reconstruction of source, liquidation of source, allocation of new source, etc.). Each initial measure $\lambda \in \Lambda$ mapping Φ onto itself ($\lambda : \Phi \rightarrow \Phi$), and the two values $\Gamma_1(\lambda)$ and $\Gamma_2(\lambda)$ of investments and annual cost of implementing the given measure are put into correspondence with each initial measure.

Let Φ_0 be the subset of Φ ($\Phi_0 \subset \Phi$) consisting of existing on-site sources of emission. We denote the vector criterion function $\bar{E}$ on Φ as

$$\bar{E}(\tilde{\Phi}) = \sum_{\bar{\varphi} \in \tilde{\Phi}} \bar{E}(\bar{\varphi}) \tag{4.2}$$

where

$$\tilde{\Phi} \subset \Phi, \qquad \bar{E}(\bar{\varphi}) = \{E_q(\bar{\varphi})\}_{q=1}^{Q} \tag{4.3}$$

The value $E_q(\bar{\varphi})$ is the q-th criterion estimation for the source $\bar{\varphi}$. The criteria estimations $E_q(\bar{\varphi})$ represent the on-site surface air pollution level. The purpose of atmospheric protection measures is to minimize these values for the entire set Φ.

The modeling site is represented by a regular grid of some specific grid step. The calculation of its criteria estimations can be made as follows

$$E_q(\bar{\varphi}) = \sum_{\varrho \in P_q(\bar{\varphi})} e_q(\bar{\varphi}, \varrho) \tag{4.4}$$

where

ϱ is the cell of the regular grid,

$P_q(\bar{\varphi})$ is the subset of cells within the $\bar{\varphi}$ source's impact described by the q-th criterion,

$e_q(\bar{\varphi}, \varrho)$ is the contribution of the $\bar{\varphi}$-th source to the pollution of the ϱ-th cell described by the q-th criterion.

Thus, the simulation site pollution can be presented as a set of maps of spatially-distributed data, each map corresponding to the criterion estimation

$$E_q(\tilde{\Phi}) = \sum_{\bar{\varphi} \in \tilde{\Phi}} \sum_{\varrho \in P_q(\bar{\varphi})} e_q(\bar{\varphi}, \varrho) \tag{4.5}$$

The basic case that exists on a given modeling site for the given set of sources Φ_0 can be estimated by

$$E(\Phi_0) = \sum_{\varphi \in \Phi_0} \bar{E}(\varphi) \tag{4.6}$$

A special set of models is used for the evaluation of each component $\bar{E}(\bar{\varphi})$. This set consists of pollutant transport models, wet and dry deposition models, and elements of ecological and economic systems' response to atmospheric pollution.

The simulation process forms various cases based on the initial set of sources Φ_0 and the initial set of measures Λ. The set Φ_0 maps onto some final set of cases $\{\Phi_*\}$, which allows some interpretation. Each of these cases is efficient from the criterion function $\bar{E}$. Generally, the analysis and exhaustive search of $2^{\Gamma(\Lambda)}$ cases forms the set of initial measures mapping Φ_0 onto Φ_*, where $\mu(\bullet)$ is the set power. The problem is to define the calculation algorithm to find efficient cases within an acceptable time span under large powers of $\mu(\Lambda)$ and $\mu(\Phi_0)$. The scheme presented below achieves this goal.

Let us choose efficient initial measures from Λ, i.e. the measures λ for which at least one criterion estimation q exists

$$E_q(\lambda(\Phi_0)) < E_q(\Phi_0) \tag{4.7}$$

The selected measures form the set of elementary measures Λ' that can be divided into the disjoint subsets

$$\Lambda' = \bigcup_{l=1}^{L} \Lambda_l \tag{4.8}$$

This division cannot be formalized, but one can state that the measures included in one of the subsets Λ_l do not change sources, which are transformed by measures from other subsets.

For each subset Λ_l there are so-called "combined measures"

$$\kappa = \sum_{i \in I_l} \lambda_i \tag{4.9}$$

where

$$\kappa(\tilde{\Phi}) = \bigcup_{i \in I_l} \lambda_i(\tilde{\Phi}) \tag{4.10}$$

$$\Gamma_p(\kappa) = \sum_{i \in I_l} \Gamma_p(\lambda_i) \qquad (p = 1,2) \tag{4.11}$$

and I_l is some feasible subset of measure indices included in Λ_l. It should be mentioned that an implementation feasibility check is made while the formation of combined measures is performed for each group Λ_l. The combined measures set convolution is further made by solving $2L$ problems of the following type.

For each pair (q,p), where q is the criterion estimation and p is the number of expenditures, such combined measures are defined on each subset Λ_l that results from the comparison procedures. The measure κ' is excluded if there exists a measure κ'' such that

$$\Gamma_p(\kappa') \geq \Gamma_p(\kappa'') \tag{4.12}$$

and

$$E_q(\kappa'(\Phi_0)) \geq E_q(\kappa''(\Phi_0)) \tag{4.13}$$

Therefore, each group Λ_l and each pair (q,p) is put into correspondence with the combined measures set $\Lambda_l(q,p)$, where E_q increases monotonically as a function of Γ_p.

In order to form the optimized combined measures set for criterion q, expenditures p, and expenditure limit Γ_p^*, the following problem is solved:

$$\sum_{l=1}^{L} E_q(\kappa_l(\Phi_0)) \rightarrow \min \tag{4.14}$$

for

$$\sum_{l=1}^{L} \Gamma_p(\kappa_l(\Phi_0)) \leq \Gamma_p^* \tag{4.15}$$

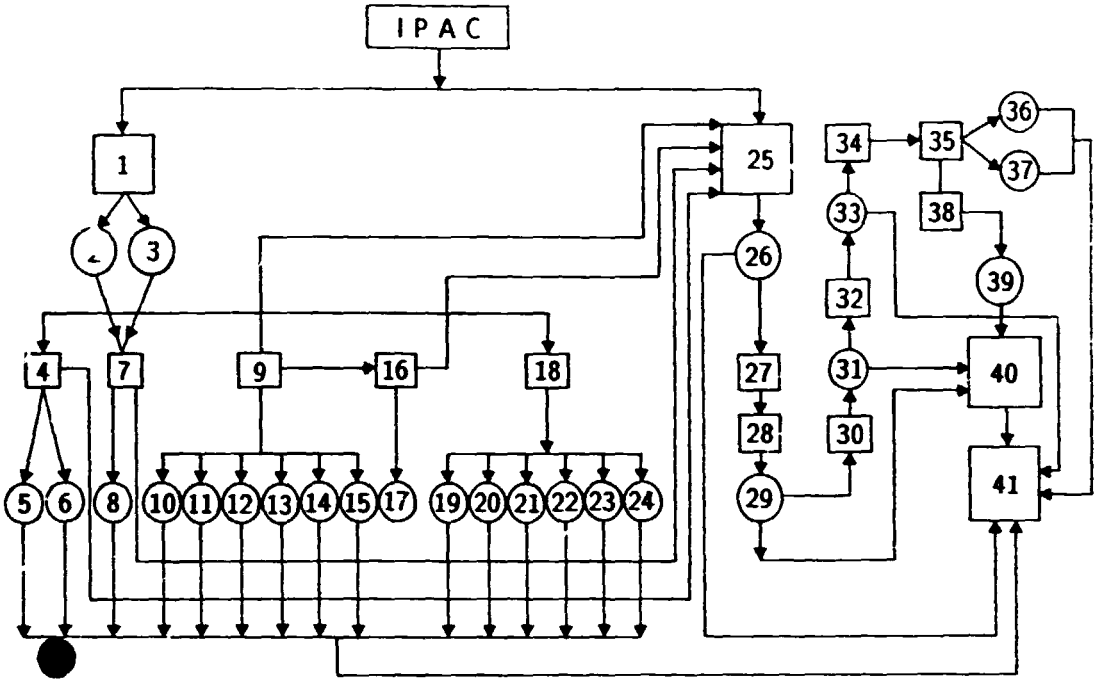


Fig. 4.1: IPAC implementation structure.

As a result, $2L$ discrete monotonic functions $F_q(\Gamma_p^*)$ are identified. The values of these functions represent the criteria estimations for the optimized strategies for reducing pollution under criterion q and expenditures p.

Let us consider the optimized set of atmospheric protection strategies that includes the values of the discrete functions $F_q(\Gamma_p^*)$. The combined measures set of Γ_1 and Γ_2 values that transform the basic case Φ_0 into the final case Φ_* with criterion estimations $\{E_q(\Phi_*)\}$ could be put into correspondence with each of the strategies. The vector $R = \{\Gamma_1, \Gamma_2, E_1, E_2, \ldots, E_Q\}$ of dimension $Q + 2$ describes one possible efficient expenditure distribution for atmospheric protection strategies.

A further convolution of the competitive atmospheric protection strategies $\{R\}$ could be based on a decision maker (DM) oriented procedure of multicriteria optimization. This procedure would present the "best strategies" based on the priorities and wishes of the DM. The DM would then choose what he considered the most appropriate strategy.

4.2 IPAC Implementation Structure

The general mathematical concepts introduced above have been implemented in the IPAC software system, running on the IBM PC/AT class of personal computers. The structure of this system is presented in Fig. 4.1.

The numbers designated in Fig. 4.1 represent the following:

1) Block of organization, following the development of data bank.
2) Bank of environmental and climatic characteristics.
3) Bank of parameters of stationary atmospheric pollution sources.
4) Block for modeling structure and spatial distribution of economic damage resulting from atmosphere pollution.
5) Assessment of economic damage for each source and pollutant.

(6) Spatial distribution of economic damage for each pollutant and total.

(7) Block for modeling of pollutant dissipation in the atmosphere over a city or industrial center.

(8) Pollutant concentration fields over a city or industrial center.

(9) Block for modeling sulfur compounds transport, dry and wet deposition for a mesoscale region, and sulfur exportation.

(10) Mean annual SO_2 concentration field.

(11) Mean annual SO_4^{2-} concentration field.

(12) Mean annual sulfur compounds dry deposition field.

(13) Mean annual sulfur compounds wet deposition field.

(14) Mean annual sulfur compounds total deposition field.

(15) Assessment of sulfur exportation out of a region on eight sectors and of total exportation.

(16) Block for modeling index of potential damage to coniferous forests in a region due to sulfur compounds total deposition.

(17) Spatial distribution of the index of potential damage to coniferous forests.

(18) Block for modeling nitrogen compounds transport, dry and wet deposition for a mesoscale region, and nitrogen exportation.

(19) Mean annual nitrogen compounds in gas concentration field.

(20) Mean annual nitrogen compounds in aerosol concentration field.

(21) Mean annual nitrogen compounds in dry deposition field.

(22) Mean annual nitrogen compounds in wet deposition field.

(23) Mean annual nitrogen compounds in total deposition field.

(24) Assessment of nitrogen exportation out of a region on eight sectors and of total exportation.

(25) Block for modeling parameters of initial atmospheric protection actions.

(26) Bank of initial atmospheric protection actions.

(27) Block of selection criteria of the efficiency of atmospheric protection efforts.

(28) Block of organization of the bank of actions efficient enough for selected mode of criterion.

(29) Bank of actions efficient for selected mode of criterion.

(30) Block for modeling permissible technological chains for decreasing wastes from sources and for analyzing their efficiency for selected mode of criterion.

(31) Efficient series of actions for each source (initial information for an optimization model).

(32) Block for modeling the optimum strategies of the atmospheric protection efforts for selected mode of criterion.

(33) Information on parameters of the optimum strategy for the mode of criterion.

(34) Block of selection (the specific optimum strategy).

(35) Block of organization (the series of the atmospheric protection actions corresponding to the optimum strategy selected).

(36) The optimum strategy for achieving a predetermined norm of the air basin state.

(37) The optimum strategy for distribution of expenses of the atmospheric protection actions with a predetermined limit of resource.

(38) Block of multicriteria optimization.

(39) Set of multioptimal strategies of air protection.

(10) Selection of multioptimal strategy by decision maker.

(11) Block of listing register.

4.3 Estimation Model of Maximum Concentrations of Surface Pollutants in Cities

Concentrations of surface pollutants from an emission source at any urban point are estimated on the basis of the analytical solution of the atmospheric diffusion equation (Beryland, 1985) under the following conditions:

- atmospheric pollutant dispersion over a period comparable to the time of transport from the source to the given point in a stationary process (Marchuk, 1989);
- the underlying surface totally reflects the pollutant, i.e. it does not interact with the soil, does not accumulate, and turbulent air flows return it to the atmosphere;
- the vertical component of the wind speed is zero (in the case of a light pollutant possessing no transport speed of its own); in the case of a heavy pollutant, the gravitational deposition rate is taken into account;
- the effective emission source height is used (corrected for the thermal plume rise).

Surface pollutant concentrations averaged at 20–30 minutes are determined for so-called "normal unfavorable weather conditions" occurring during an unbalanced (unstable) stratification of the atmosphere, i.e. during an intensive vertical mixing throughout the boundary layer (about 1 km), which differs essentially from the zero temperature gradient. In this case it is assumed that the vertical turbulent exchange coefficient in the surface layer increases linearly with height (exchange model), the wind speed varies with height according to the power law, and the horizontal turbulent exchange coefficient is proportional to the wind speed. Thus the parameters governing pollutant dispersion conditions are functions of the wind speed and, for each emission source, a "dangerous" speed U_{iM} can be calculated at which the surface concentration along the plume axis (i.e., when the wind is directed from the source to the calculated point) has the maximum value.

In cases where the surface concentration is estimated for a group of sources each having its own dangerous speed and direction of wind (with the plume axis direction being determined by the source and calculated point coordinates), assumptions should be made based on those conditions common to all emittants.

In the dispersion block, the directions of the wind blowing from the source are selected with a certain fixed angular step (usually 10°, which corresponds to 36 directions providing the required accuracy of maximum concentration assessment). The common dangerous wind speed for Φ emittants of the k-th pollutant is estimated as a mean weighted value (the modified dangerous wind speed)

$$U^{(k)} = \frac{\sum_{\bar{\varphi}\in\Phi} C^{(k)}_{\bar{\varphi}M} U_{\bar{\varphi}M}}{\sum_{\bar{\varphi}\in\Phi} C^{(k)}_{\bar{\varphi}M}} \tag{4.16}$$

where

$C^{(k)}_{\bar{\varphi}M}$ – maximum concentration of the k-th pollutant from the $\bar{\varphi}$-th source along the plume axis, achieved at dangerous wind speed $U_{\bar{\varphi}M}$.

Then the maximum concentration of the k-th pollutant emitted from Φ sources under normal unfavorable weather conditions at a calculated point with coordinates (x, y) is

$$C^{(k)}(x,y) = \max_{\beta, U^{(k)}} \sum_{\bar{\varphi}\in\Phi} C^{(k)}_{\bar{\varphi}} \left(x, y, \beta, U^{(k)}\right) \tag{4.17}$$

where

$C_{\bar{\varphi}}^{(k)}$ – surface concentration produced by the $\bar{\varphi}$-th source at wind direction β and dangerous wind speed $U^{(k)}$.

The accuracy of the $C^{(k)}(x,y)$ estimates depends on the adequacy of the selection of the wind speed and the direction at which the total surface concentration is calculated by the formula.

Normal unfavorable weather conditions are relatively frequent during the year (unlike anomalous unfavorable weather conditions, e.g., inversions with calms, fog, etc.). Mean diurnal concentrations do not exceed mean daily MPCs (maximum permissible concentrations) if surface concentrations calculated for normal unfavorable weather conditions do not exceed single maximum permissible sanitary standards averaged over 20 minutes. (The opposite statement is not true.) Therefore, pollutant concentrations are calculated for normal unfavorable conditions as a criterion for the respective assessment.

Where the calculation model of maximum concentrations under normal unfavorable conditions is summarized on the basis of numerical methods, correlations are obtained for the determination of the "dangerous" wind speed (at a windcock level – usually 10 m above the ground) for the $\bar{\varphi}$-th emission source m/s depending on parameters v_M:[1]

$$U_M = \begin{cases} 0.5 & \text{if } v_M \le 0.5 \\ v_M & 0.5 \le v_M \le 2 \\ v_M(1 + 0.12\sqrt{f}) & v_M > 2 \end{cases} \tag{4.18}$$

where

$$f = 1621.14 \frac{V^2}{H^2 D^3 \Delta T} \tag{4.19}$$

and

$$v_M = 0.65 \frac{\sqrt[3]{V \Delta T}}{H} \tag{4.20}$$

In these formulae

V – rate of the emission (m^3/s),

H – geometrical height of emission source (m),

D – diameter of source outlet (m),

ΔT – temperature difference between the emitted gas and ambient air (°C).

If $\Delta T \le 0$ or $f \ge 100$, the source emission is considered cold and U_M is determined using the following formulae:

$$U_M = \begin{cases} 0.5 & \text{if } v_M \le 0.5 \\ v_M & 0.5 < v_M \le 2 \\ 2.2 v_M & v_M > 2 \end{cases} \tag{4.21}$$

where

$$v_M = 1.655 \frac{V}{DH} \tag{4.22}$$

The maximum concentration (mg/m^3) is reached at the "dangerous" wind speed U_M at the distance X_M from the source along the plume axis:

for warm emissions:

$$C_M = \frac{A \cdot M \cdot F \cdot m \cdot n}{H^2 \sqrt[3]{V \Delta T}} \tag{4.23}$$

for cold emissions:

$$C_M = 0.125 \frac{A \cdot M \cdot F \cdot D \cdot n}{V \sqrt[4]{H^3}} \tag{4.24}$$

where

[1] To simplify the formulae, the φ-th source index will be omitted whenever possible.

A – coefficient depending on the temperature stratification of the atmosphere and governing the conditions for the vertical and horizontal atmospheric dispersion of noxious materials $\left(s^{2/3} \cdot mg \cdot degr.^{1/3}/g\right)$;

M – pollutant mass emitted into the atmosphere per unit time (g/s);

F – a dimensionless coefficient taking into account the vertical component of the pollutant transport speed (deposition rate) in the atmosphere;

m, n – dimensionless coefficients taking into account the conditions for gas release from the source outlet

$$m = \frac{1}{0.67 + 0.1\sqrt{f} + 0.34\sqrt[3]{f}} \tag{4.25}$$

$$n = \begin{cases} 3 & \text{if } v_M \le 0.3 \\ 3 - \sqrt{(v_M - 0.3)(4.36 - v_M)} & \text{if } 0.3 < v_M \le 2 \\ 1 & \text{if } v_M > 2 \end{cases} \tag{4.26}$$

The coefficient A, which also depends on the surface layer height and the underlying surface roughness, is calculated for open, flat terrains in various geographical regions and, accounting for relief correction, varies from 100 to 260. A can be taken based on the similarity of the climatic characteristics of the turbulent regime.

The parameter F differs for gases, light aerosols, and TSP. It is dependent on the particle size distribution which is related to the performance of TSP collecting facilities in cases where they are installed at the source. For gases and aerosols (with a settling rate below 5 m/s) $F = 1$; for TSP which is transported as a heavy pollutant, $F = 2$, 2.5 and 3 if the performances of TSP collecting facilities are over 90%, 75–90% and below 75%, respectively.

The maximum surface pollutant concentration C_M along the plume axis (in the direction of an average wind) is achieved at distance X_M from the emission source (m):

$$X_M = \begin{cases} dH & \text{if } F = 1 \\ \dfrac{5 - F}{4} dH & \text{if } F \ge 2 \end{cases} \tag{4.27}$$

The parameter d is calculated as a function of v_M:

for warm emissions:

$$d = \begin{cases} 4.95 v_M (1 + 0.28\sqrt[3]{f}) & \text{if } v_M \le 2 \\ 7\sqrt{v_M}(1 + 0.28\sqrt[3]{f}) & \text{if } v_M > 2 \end{cases} \tag{4.28}$$

for cold emissions:

$$d = \begin{cases} 11.4 v_M & \text{if } v_M \le 2 \\ 16.1\sqrt{v_M} & \text{if } v_M > 2 \end{cases} \tag{4.29}$$

If the dangerous wind speed is taken as the modified value, a deviation of U_M from $U^{(k)}$ is possible for each $\bar{\varphi}$-th emission source. In this case, the maximum surface concentration is

$$C_{MU} = r \cdot C_M \tag{4.30}$$

where

r – dimensionless quantity determined depending on the relation $q = U^{(k)}/U_M$

$$r = \begin{cases} 0.67q + 1.67q^2 - 1.34q^3 & \text{if } q \le 1 \\ \dfrac{3q}{2q^2 - q + 2} & \text{if } q > 1 \end{cases} \tag{4.31}$$

Surface pollutant concentrations in the atmosphere along the plume axis at distance x from the source are calculated by the following formula

$$C_x = s_1 \cdot C_{MU} \tag{4.32}$$

where

s_1 – dimensionless quantity, which depending on the relation

$$z = \frac{x}{X_M} \tag{4.33}$$

satisfies the conditions

$$s_1 = \begin{cases} 3z^4 - 8z^3 + 6z^2 & \text{if } z \leq 1 \\ 1.13/(0.13z^2 + 1) & \text{if } 1 < z \leq 8 \\ z/(3.58z^2 - 35.2z + 120) & \text{if } z > 8 \text{ and } F = 1 \\ 1/(0.1z^2 + 2.47z - 17.8) & \text{if } z > 8 \text{ and } F \geq 2 \end{cases} \tag{4.34}$$

When the calculated point is shifted perpendicular to the plume axis at distance y, the surface pollutant concentration in the atmosphere is

$$C_y = s_2 \cdot C_x, \tag{4.35}$$

where

s_2 – dimensionless quantity given for wind speed U_M and relation $g = y/x$

$$s_2 = \frac{1}{(1 + 8.4U_M g^2)(1 + 28.2U_M^2 g^4)} \tag{4.36}$$

Thus, the surface pollutant concentration at a point with coordinates (x, y) from the $\bar{\varphi}$-th emission source, dangerous wind speed $U^{(k)}$ and a fixed transport direction β (along the plume axis x) is

$$C_{\bar{\varphi}U}(x, y) = r \cdot s_1 \cdot s_2 \cdot C_M \tag{4.37}$$

The distance X_{MU} at which the surface concentration C_{MU} is achieved is

$$X_{MU} = p \cdot X_M \tag{4.38}$$

where

$$p = \begin{cases} 3 & \text{if } q \leq 0.25 \\ 8.43(1 - q)^5 + 1 & \text{if } 0.25 < q \leq 1 \\ 0.32q + 0.68 & \text{if } q > 1 \end{cases} \tag{4.39}$$

To determine the maximum surface concentration fields for several pollutants in a city whose territory is represented by a regular grid, one usually has to calculate about 1000 matrices, each containing over 1000 elements. Such calculations, associated with the exhaustive search of wind directions and speeds, require much computer time. Therefore, methods that prescribe an "expediency constant" $\epsilon^{(k)}$ are employed to reduce calculation time. The constant is set equal to $0.05P^{(k)}$ where

$P^{(k)}$ – maximum permissible atmospheric concentration of the k-th pollutant (sanitary standard).

When calculating surface concentrations at each algorithm step, the following condition should be fulfilled:

$$C_{\bar{\varphi}U}^{(k)} > \epsilon^{(k)} \tag{4.40}$$

If this condition cannot be fulfilled, calculations for the $\bar{\varphi}$-th source at a given algorithm step are interrupted.

The maximum concentration $C_{\bar{\varphi}M}^{(k)}$ is tested. If for the $\bar{\varphi}$-th source

$$C_{\bar{\varphi}M}^{(k)} < \epsilon^{(k)} \tag{4.41}$$

the source is not considered for the k-th pollutant. Thus, $U^{(k)}$ is determined taking into account only emittants for which the relation is not fulfilled, so the parameter Φ (the number of sources included in calculations for the k-th pollutant) can differ from the total number of emission sources considered in the model.

The value $C_{\bar{\varphi}MU}^{(k)}$ is tested. If for the $\bar{\varphi}$-th source

$$C_{\bar{\varphi}MU}^{(k)} < \epsilon^{(k)} \tag{4.42}$$

the source is also omitted from further calculations for the k-th pollutant.

The radius of the pollution zone $R_{\bar{\varphi}x}^{(k)}$ is established for each $\bar{\varphi}$-th source at

$$s_1 = 0.05\frac{P^{(k)}}{C_{\bar{\varphi}MU}^{(k)}} \tag{4.43}$$

The value $R_{\bar{\varphi}x}^{(k)}$ determines the coordinates of the calculated points of the urban regular grid at which concentrations are to be calculated. The application of pollution zone radii allows a drastic reduction in the number of calculated points due to the peculiarities of high and low emission rates.

The flux dispersion angle perpendicular to the plume axis is established at

$$s_2 = 0.05\frac{P^{(k)}}{C_x} \tag{4.44}$$

The value $g = tg\alpha$ is determined, where

α - the angle required.

Thus, the $\bar{\varphi}$-th source pollution zone is a sector with angle α of a circle with radius $R_{\bar{\varphi}x}^{(k)}$. (In the upwind direction (at $x < 0$), pollutant concentrations are 0.) The active pollution zone from a source is presented in Fig. 4.2

The concentration of pollutant k for point $\varrho = (x, y)$ of the regular grid representing a city on the source set Φ is

$$C^{(k)}(\varrho) = \sum_{\varphi \in \Phi} C_{\bar{\varphi}}^{(k)}(\varrho) \tag{4.45}$$

The corresponding index (element of criterion function $\bar{E}(\Phi)$) is

$$E_q^{(k)} = \sum_{\varrho} \frac{C^{(k)}(\varrho)}{P^{(k)}} \qquad \text{for } \frac{C^{(k)}(\varrho)}{P^{(k)}} > 1 \tag{4.46}$$

The value $E_q^{(k)} \leq 1$ is a satisfactory state of an air basin of a city for the k-th pollutant. For several pollutants considered simultaneously, the satisfactory state is achieved when

$$E_{q^*} = \sum_{k} E_q^{(k)} \qquad \text{for } E_{q^*} \leq 1 \tag{4.47}$$

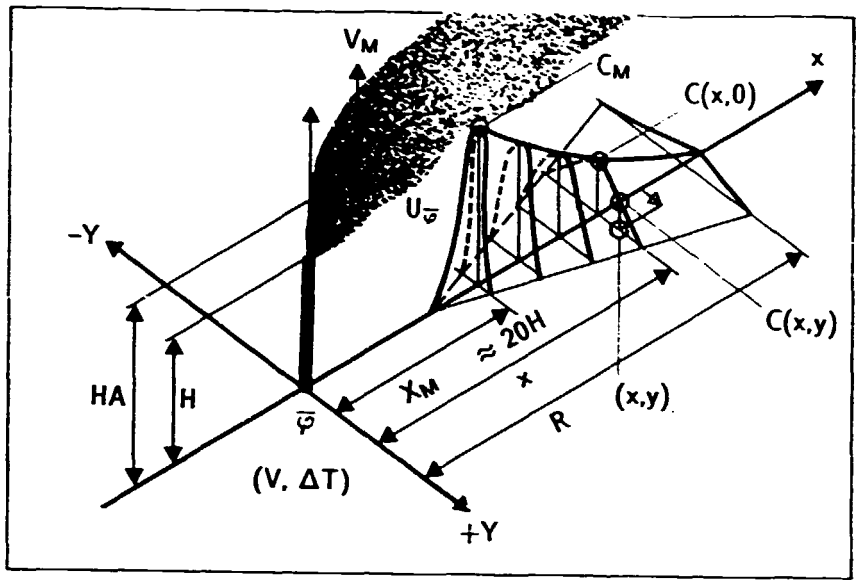


Fig. 4.2: Active pollution zone from a source.

4.4 Meso-Scale Models of Transport and Transformation of Sulfur Dioxide in the Atmosphere

Meso-scale models that allow one to compute concentration, dry and wet deposition of atmospheric SO_2 and SO_4^{2-}, as well as sulfur transport out of the region, have been developed, algorithmically represented, and tested in the IPAC subsystem "Region". The model enables the criteria for minimizing the total deposition and removal of sulfur compounds to develop, as well as to enter, the automated complex of blocks presenting the atmospheric pollutant effects on the regional ecosystems which are constructed according to the "dose–effect" principle.

The models of transport and transformation of sulfur compounds in the atmosphere meet the following requirements:

- the spatial scale of pollutant transport in the atmosphere amounts to several hundred kilometers and corresponds to the size of a territorial administrative unit (meso-scale level);
- the time resolution equals a year (as a rule, the technical and economic parameters of air protection measures that form the basis of the optimization analysis refer to this very period);
- the models have been realized as climatic ones, i.e., pollutant transport is computed for meteorological conditions averaged over a long period (10 years and more) rather than within the fields of real (current) wind and precipitation; this is related to the fact that the efficiency of air protection measures is estimated for one year or more;
- the period of calculation using a personal computer is relatively short, since the optimization is carried out iteratively;
- pollution levels are computed for each of the regional emission source where air protection measures are carried out;
- temporal variations of concentration were calculated within the coordinate system related to the moving mass of the pollutant (Lagrangian approach).

The region is represented as a regular grid whose square rasters usually are of dimension 10×10 km. A climatic wind rise introduced for the considered region presents probabilities of various wind directions and a mean velocity of pollutant transport in the atmosphere. Transport velocity in the mixing layer, varied by wind directions, is calculated as an average. It is assumed that the wind velocity varies exponentially with height, the vertical exchange coefficient increases linearly with height in the mixing layer and remains constant above it, and the horizontal exchange coefficient varies with height like the wind velocity. The wind and precipitation field in the region is homogeneous.

The constants of dry and wet sulfur deposition from the atmosphere, the chemical transformation of sulfur dioxide into sulfate, and the height of the mixing layer are introduced as mean annual values (averaging period being equal to 10 years) and are constant over the region's territory.

The wet deposition of sulfur compounds and the chemical transformation of sulfur dioxide into sulfate are described as linear processes. No consideration is taken of the relief of the region. Sulfur dioxide emission shows no variations throughout the year.

The assessment of mean atmospheric pollution using trajectory models is usually carried out by successively computing the concentrations and depositions along the observed trajectories and averaging the obtained results. Since the period of a year and more includes tens of thousands of air trajectories and the model is to be used in an iterative optimizing regime, such an approach to pollution assessment is unacceptable. Therefore, real trajectories are substituted by a number of straight ones, each being realized with a certain probability $\bar{\beta}_m$. The possibility to consider straight trajectories is related to the meso-scale of pollutant transport in the atmosphere.

The model assumes a one-layer wind; in the mixing layer (at height H_m) pollutants are assumed to mix instantly.

Sulfur emission is represented as a sequence of portions ejected from the source in discrete time intervals $t = i \cdot T$, $i = \overline{1,I}$ where T (min) is a time step and I is the number of the step at which the observation ends. The time step is selected so that (1) the distance passed by a portion during step T is less than the dimensions of the raster, and (2) pollutant portions are superimposed on each other, forming a continuous stream.

The sequence of portions emitted by the source forms a stream. The location (coordinates) of the center of the portion and its characteristics (dimensions, dry and wet deposition, chemical transportations) are measured using the model for a discrete time period. Successive locations of the portion's center in discrete time periods represent the trajectory of the portion's movement. The stream is stationary during intraregional transport. It follows from the state of being stationary that, to calculate the fields of sulfur compound deposition and content, it is sufficient to trace the locations and characteristics of a single portion in the stream. The model considers $m = \overline{1,48}$ stationary locations of the stream, corresponding to 48 wind directions.

The spatial resolution of the model is represented by the dimensions of the raster. Surface concentrations and deposition (averaged over the raster) are calculated in each raster at each m-th direction of the stream. The results are then averaged in all directions to obtain the annual assessments.

The well-known process of the chemical transformation of SO_2 is presented in Fig. 4.3. Wind velocity varies with height z by an exponential law

$$V = V_0 \left(\frac{z}{z_0} \right)^{P_S} \tag{4.48}$$

Then mean transport velocity in the mixing layer (at a height H_M) is equal to

$$\bar{V} = \frac{1}{H_M} \int_0^{H} V_0 \left(\frac{z}{z_0} \right)^{P_S} dz = \frac{V_0}{P_S + 1} \cdot \left(\frac{H_M}{z_0} \right)^{P_S} \tag{4.49}$$

where P_s is the atmosphere stratification parameter in the region and V_0 is the wind velocity near the ground at height z_0 in a region. The X- and Y-axis components of the transport velocity

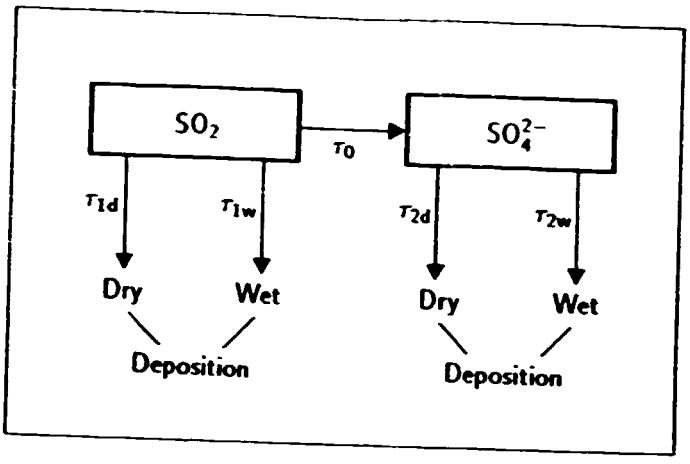


Fig. 4.3: Chemical transformation of SO_2 in the model.

the atmosphere in m-direction are equal to

$$\bar{v}_{xm} = \bar{V} \cos \alpha_m \tag{4.50}$$

$$\bar{v}_{ym} = \bar{V} \sin \alpha_m \tag{4.51}$$

respectively, where α_m is the angle between the X-axis and the m-th wind direction in the coordinate system selected for the region.

The dry deposition of SO_2 and SO_4^{2-} is also described as a linear process. At the initial moment, the portion is uniformly distributed over the raster, its centers coinciding.

The following parameters are calculated at each i-th step at the m-th wind direction (stream location).

- Coordinates of the portion center

$$x_{im} = x_{i-1,m} + \bar{v}_{xm} \tag{4.52}$$

$$y_{im} = y_{i-1.m} + \bar{v}_{ym} \tag{4.53}$$

Horizontal widening of the stream is taken into account only if it is directed across the portion movement; horizontal diffusion at each step is shown in Fig. 4.4

$$x_{im} = x_{i-1,m} + 0.2\,|\bar{v}_{ym}| \tag{4.54}$$

$$y_{im} = y_{i-1,m} + 0.2\,|\bar{v}_{ym}| \tag{4.55}$$

- Masses of SO_2 ($j = 1$) and SO_4^{2-} ($j = 2$) remaining in a portion in the i-th interval

$$M_{ji} = M_{j(i-1)} - \Delta M_i - \sum_{\varrho} D_{ji}^{\varrho} - \sum_{\varrho} W_{ji}^{\varrho} \tag{4.56}$$

where $\Delta M_i = M_{j(i-1)}/\tau_0$ is the mass of SO_2 that chemically transformed into SO_4^{2-}, and τ_0 is the SO_2 residence time in the atmosphere relative to the chemical transformation.

- Dry deposition of SO_2 and SO_4^{2-} on the ϱ-th raster in a year

$$D_{ji}^{\varrho} = \frac{\tau}{\tau_{jw}} \sum_m \beta_m \sum_i \frac{M_{j(i-1)}}{L_{im} \cdot S_{\varrho}} \qquad j = 1, 2 \tag{4.57}$$

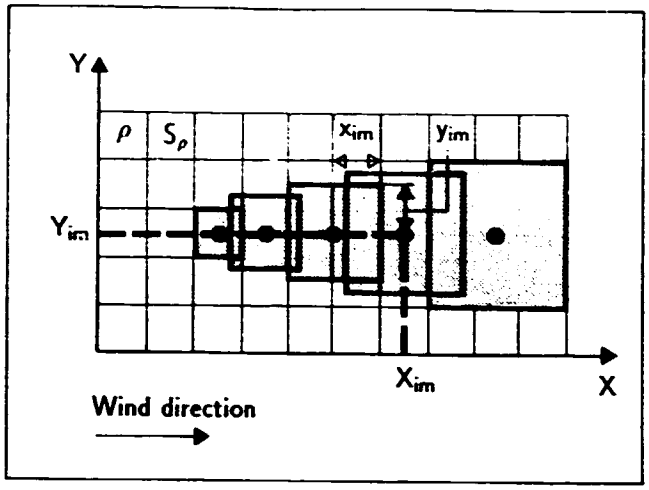


Fig. 4.4: The portion movement.

- Wet deposition of SO_2 and SO_4^{2-} on the ϱ-th raster in a year

$$W_{ji}^{\varrho} = \frac{\tau}{\tau_{jd}} \sum_m \bar{\beta}_m \sum_i \frac{M_{j(i-1)}}{L_{im} \cdot S_\varrho} \qquad j = 1,2 \tag{4.58}$$

In these equations, τ is the duration of a year in T intervals; τ_{jd} and τ_{jw} are the residence times of SO_2 and SO_4^{2-} relative to dry and wet deposition from the atmosphere, respectively; L_{im} is the number of rasters in a region "stricken" by a portion in the i-th interval in the m-th direction; S_ϱ is a square of a grid raster.

It is assumed in the model that dry and wet deposition of SO_2 and SO_4^{2-} from the portion contribute to the deposition of a given raster only in cases where its center lies within the portion, i.e., is "covered" by it.

SO_2 and SO_4^{2-} lifetimes in the atmosphere in relation to wet deposition are expressed in the model as

$$\tau_{jw} = \frac{\tau}{k_j \cdot U \cdot b}, \qquad j = 1,2 \tag{4.59}$$

where k_j are the coefficients of SO_2 and SO_4^{2-} washout from the atmosphere, U is the amount of precipitation in a region, and b is a part of wet period in a year. The lifetimes in relation to dry deposition are calculated as

$$\tau_{jd} = \frac{H_M}{V_j}, \qquad j = 1,2 \tag{4.60}$$

where V_j are SO_2 and SO_4^{2-} dry deposition rates, respectively.

Testing the conditions for further observation of the portion, the observation ends in cases where:

- the portion has left the region (coordinates of its center do not belong to the region),
- the sulfur content in the portion is below the value

$$\sum_j \frac{M_{ji}}{L_{im} \cdot S_\varrho} < \epsilon \tag{4.61}$$

Thus, the average wet and dry deposition of sulfates on a p-raster in a year for a set of sources Φ is

$$N_s^{\varrho} = \sum_i \sum_j \left(D_{ji}^{\varrho} + W_{ji}^{\varrho} \right) \tag{4.62}$$

the summary deposition of sulfates in a year is expressed as

$$N_s = \sum_{\varrho} N^{\varrho} \tag{4.63}$$

the summary exportation sulfates from a region are expressed as

$$N_{SE} = M_{SO_2} - N_{sd} \tag{4.64}$$

and the mean annual surface concentrations of SO_2 and SO_4^{2-} over a ϱ-raster can be expressed as

$$C_j^{\varrho} = \frac{\sum_i D_{ji}^{\varrho}}{V_j \cdot \tau} \tag{4.65}$$

4.5 Meso-Scale Model of Transport and Transformation of Nitrogen Oxide and Nitrogen Dioxide in the Atmosphere

To calculate these parameters, the chemical transformation block of the meso-scale sulfur model is modified for the emissions NO_x in the chain $NO \rightarrow NO_2 \rightarrow HNO_3 \rightarrow NO_3^-$. Fig. 4.5 presents the chemical transformation process that is used for modeling. The dry (D_{ji}^{ϱ}) and wet (W_{ji}^{ϱ}) depositions of NO ($j = 1$), NO_2 ($j = 2$), HNO_3 in gas ($j = 3$), HNO_3 in aerosol ($j = 4$), and NO_3^- ($j = 5$) on the ϱ-th raster of the regional regular grid for each i-th interval in a year are defined as follows:

$$D_{ji}^{\varrho} = \frac{1}{\tau_{(j+5)}} \cdot M_{j(i-1)} \qquad \text{for } j = \overline{1,4} \tag{4.66}$$

$$D_{5i}^{\varrho} = \frac{1}{\tau_9} \cdot M_{j(i-1)} \tag{4.67}$$

$$W_{ji}^{\varrho} = \frac{1}{\tau_{(j+8)}} \cdot M_{j(i-1)} \qquad \text{for } j = \overline{2,4} \tag{4.68}$$

$$W_{5i}^{\varrho} = \frac{1}{\tau_{12}} \cdot M_{5(i-1)} \tag{4.69}$$

The masses of nitrogen compounds remaining in a portion in the i-th interval are

$$M_{1i} = \left(1 - \frac{1}{\tau_1}\right) \cdot M_{1(i-1)} - \sum_{\varrho} D_{1i}^{\varrho} \tag{4.70}$$

$$M_{2i} = \left(1 - \frac{1}{\tau_2} - \frac{1}{\tau_3} - \frac{1}{\tau_4}\right) \cdot M_{2(i-1)} + \frac{1}{\tau_1} \cdot M_{1(i-1)} - \sum_{\varrho} D_{2i}^{\varrho} - \sum_{\varrho} W_{2i}^{\varrho} \tag{4.71}$$

$$M_{3i} = \left(1 - \frac{1}{\tau_5}\right) \cdot M_{3(i-1)} + 0.5 \cdot \left(\frac{1}{\tau_2} + \frac{1}{\tau_3} + \frac{1}{\tau_4}\right) \cdot M_{2(i-1)} - \sum_{\varrho} D_{3i}^{\varrho} - \sum_{\varrho} W_{3i}^{\varrho} \tag{4.72}$$

$$M_{4i} = \left(1 - \frac{1}{\tau_5}\right) \cdot M_{4(i-1)} + 0.5 \cdot \left(\frac{1}{\tau_2} + \frac{1}{\tau_3} + \frac{1}{\tau_4}\right) \cdot M_{2(i-1)} - \sum_{\varrho} D_{4i}^{\varrho} - \sum_{\varrho} W_{4i}^{\varrho} \tag{4.73}$$

$$M_{5i} = M_{5(i-1)} - \frac{1}{\tau_5}\left(M_{3(i-1)} + M_{4(i-1)}\right) - \sum_{\varrho} D_{5i}^{\varrho} - \sum_{\varrho} W_{5i}^{\varrho} \tag{4.74}$$

In these equations,

$$\begin{aligned} \tau_j &= \frac{H_M}{V_j} && \text{for } j = \overline{6,9} \\ \tau_j &= K_j \cdot U \cdot L && \text{for } j = \overline{10,12} \\ \tau_j &= (c_j \cdot b_j)^{-1} && \text{for } j = \overline{2,3} \end{aligned} \tag{4.75}$$

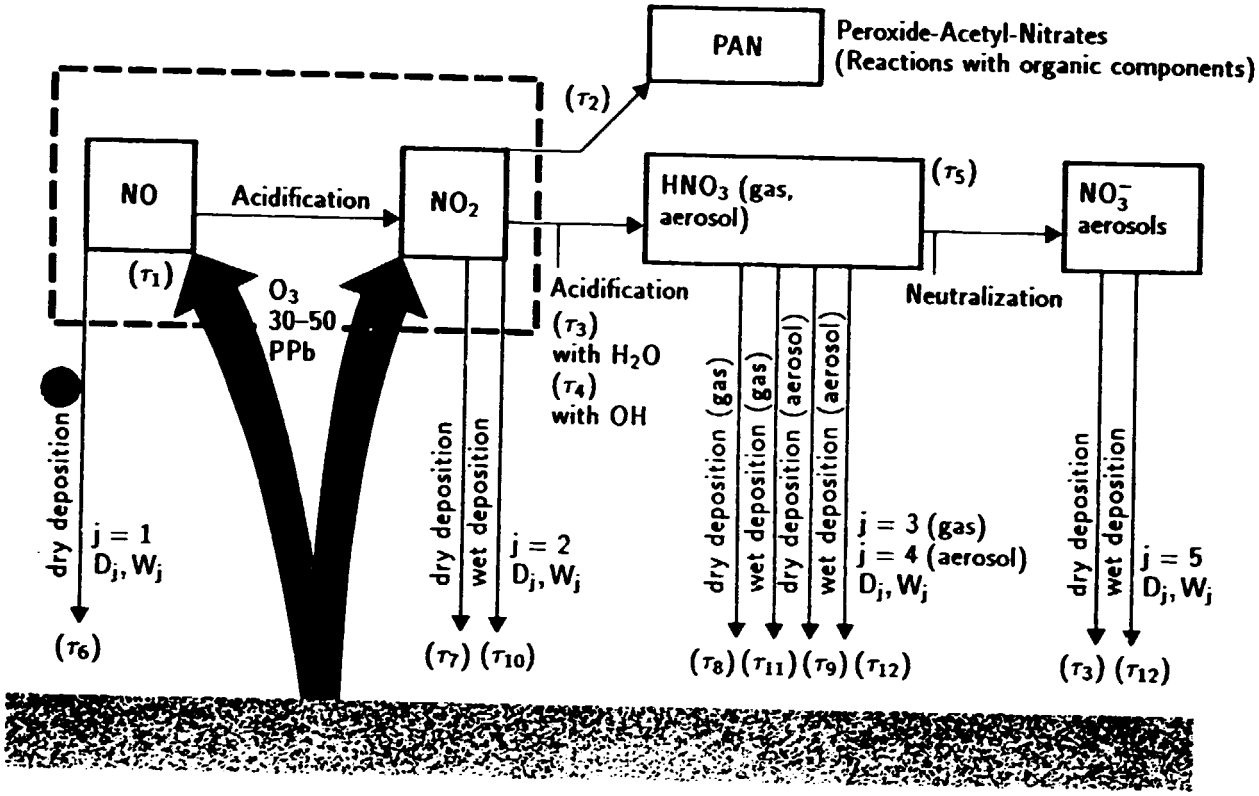


Fig. 4.5: Chemical transformation and deposition of nitrogen pollutants.

where V_j are the dry deposition rates for corresponding compounds; K_j are the coefficients of washout from the atmosphere; c_j are the typical mean annual concentrations of the chemical radicals OH and RCO_3 in the atmosphere of a region; and b_j are constants of the corresponding chemical reactions ($j = 2,3$). The parameters U and [illegible] presented in the sulfur model.

Thus, the mean annual dry and wet deposition [illegible]gen compounds on the ϱ-th raster:

$$D_j^{\varrho} = \tau \cdot \sum_m \bar{\beta}_m \sum_i \frac{D_{ji}^{\varrho}}{L_{im} \cdot S_{\varrho}} \qquad \text{for } j = \overline{1,5} \tag{4.76}$$

$$W_j^{\varrho} = \tau \cdot \sum_m \bar{\beta}_m \sum_i \frac{W_{ji}^{\varrho}}{L_{im} \cdot S_{\varrho}} \qquad \text{for } j = \overline{1,5} \tag{4.77}$$

The parameters τ, β_m, L_{im}, S_{ϱ} are defined in the sulfur model. The summary deposition of nitrates in aerosol from the portion on the ϱ-raster in a year is expressed

$$N_N^{\varrho} = \sum_{j=4}^{5} D_{ji}^{\varrho} + \sum_{j=2}^{5} W_{ji}^{\varrho} \tag{4.78}$$

The summary deposition of nitrates in aerosol on a region in a year is expressed

$$N_N = \sum_{\varrho} N_N^{\varrho} \tag{4.79}$$

and the summary nitrates in aerosol exportation from a region in a year are expressed

$$N_{NE} = M_{NO_x} - N_N - M_{PAN} \tag{4.80}$$

where $M_{PAN} = \frac{1}{\tau_2} \sum_i M_{2i}$ is the mass of Peroxide–Acetyl–Nitrates produced from the emission of NO and NO_2 as a result of a chemical reaction with organic components (in general, the radical $RCO_3 + NO_2 \rightarrow$ PAN). The mean annual surface concentrations NO, NO_2, HNO_3 in gas over the ϱ-th raster can be expressed as

$$C_j^{\varrho} = \frac{\left(\sum_i D_{ji}^{\varrho}\right)}{V_j \cdot \tau} \qquad \text{for } j = 1,2,3 \tag{4.81}$$

.6 Approximate Model for Economic Damage Estimation

The economic damage from pollution of the lower layer of the atmosphere (*Approximate economic damage estimations* ..., 1986): can be expressed as

$$Y = \gamma \times \sigma \times f \times M_c \tag{4.82}$$

where

- Y – the economic damage (monetary units/year);
- γ – the average specific economic damage (monetary units/comparison ton);
- σ – the dimensionless value characterizing the structure of recipients located in the zone of a source active pollution;
- f – the dimensionless correction for the mode of a pollutant dissipation in the atmosphere to be dependent on an active height of a source, mean annual wind velocity, and rate of admixture disposition.

For organized sources (stacks of height $H < 10$, the zone of an active pollution is represented by a circle with a center in a point of a source location and with a radius of $50H$; but for $H \geq 10$ m the zone is a ring formed by the radii

$$R_{\text{inner}} = 2 \cdot \left(1 + \frac{\Delta T}{75}\right) \cdot H, \qquad R_{\text{outer}} = 20 \cdot \left(1 + \frac{\Delta T}{75}\right) \cdot H \tag{4.83}$$

where

ΔT – the drop of temperature (in °C) between the mouth of a source and an ambient atmosphere (mean annual temperature); the denominator 75 is temperature in °C).

Emissions of pollutants in a time-interval can be compared if coefficients of toxicity a_k or coefficients of relative aggresivity A_k are used. These coefficients define the level of negative impact of the k-pollutant relative to carbon monoxide (CO). In the general case,

$$A_k = \alpha_k^{(1)} \cdot \alpha_k^{(2)} \cdot \alpha_k^{(3)} \cdot \alpha_k^{(4)} \cdot a_k \tag{4.84}$$

where

$\alpha_k^{(1)}$ – the correction for the probability of a pollutant accumulation in environmental compartments, in food chains, and of a pollutant intake into the human organism through any means other than inhalation;

$\alpha_k^{(2)}$ – the correction for a pollutant effect on various recipients other than humans;

$\alpha_k^{(3)}$ – the correction for the probable secondary discharge of a pollutant into the atmosphere;

$\alpha_k^{(4)}$ – the correction for the probable formation of secondary pollutants more dangerous than the initial pollutants.

$$a_k = \sqrt{\frac{P_{co}^{(1)} \cdot P_{co}^{(2)}}{P_k^{(1)} \cdot P_k^{(2)}}} \tag{4.85}$$

where $P^{(1)}$ and $P^{(2)}$ are the maximum occasional permissible concentration (MOPC, and the maximum permissible concentration (MPC), respectively.

Thus, the summary given mass (comparison ton/year) of pollutant emmisions to the atmosphere from the set Φ of sources can be expressed as

$$M_k = \sum_{\varphi \in \Phi} A_k \cdot M_{\varphi k}\,, \qquad M = \sum_k M_k \tag{4.86}$$

The values A_j of the most frequently occurring pollutants lie within the limits of 1 to 12×10^5.

The suggested method of calculating economic damage is addressed at particular sources and based on emission accounting and therefore keeps the advantages of the indices of the first type. However, the effect on recipients is considered only in the nearest vicinity of a source (the zone of active pollution).

4.7 Approximate Model for Calculating Potential Damage Index of Coniferous Forests

The simplest "dose effect" model permitting the calculation of the index of potential damage by sulfur compounds deposition to the coniferous forests of a region illustrates the expediency of IPAC system use to protect the atmosphere from pollution.

The method, devised at the GDR Center for Environmental Formation, that considers the ct effect of sulfur compounds deposition on coniferous forests is used for the calculation of index:

$$d_\varrho = 10 - 10 \exp\left(\frac{N_S^\varrho}{36}\right) \tag{4.87}$$

$$d = \sum_\varrho d_\varrho \tag{4.88}$$

re $0 \le d_\varrho \le 10$ is an assessment of the total sulfur atmospheric deposition on coniferous sts in a raster element ϱ. It is possible to set a coniferous forest's threshold of sensitivity to ır compounds atmospheric deposition. If this threshold value $P^{(3)}$ is known, then the index sforms to:

$$d = \sum_\varrho d_\varrho \qquad \text{for } d_\varrho > P^{(3)} \tag{4.89}$$

Choosing Optimal Strategies

ral hundred, even a thousand, pollutant emission sources are present in the territory of a real 'regi[redacted] Five to fifteen air protection measures can be implemented at each source. Thus, ıltitude of variants for protecting the air basin from pollution arises. Special optimization ithms are required for a comparative analysis of these variants.

)ptimal strategies can be selected on the basis of an algorithm that includes the following stages.

;e 1: Simulating a bank of initial measures

construction of this bank involves an analysis of each measure for reducing pollutant emis- that is technically available for the considered source. Such measures are noted by great ty, carried out for a single or several emitters and, in general, can change any parame- ıaracterizing the conditions of pollutant emission into the atmosphere of the city/region. efore, a system of models and algorithms enables the analysis of a wide range of innovations l at air basin protection, making it possible to

- change any combination of parameters characterizing a single emitter;
- change any combination of parameters characterizing several emitters;
- eliminate the emitter;
- eliminate the emitter with partial or complete transfer of its functions to other emission sources located or newly disposed in the territory of a city/region;
- remove one or more emitters to another city/region;
- select the least dangerous relocation of one or more emitters in a city/region.

ıe optimization algorithm considered suggests subdividing the bank of initial measures ouping together pollution sources with similar technological processes (any air protection re is definitely related to an emitter). It specifies no strict requirements on determining mposition of these groups; however, dividing the bank according to some principle (e.g., rial) expedites the interpretation of the results obtained at subsequent algorithm stages. t L be the number of groups in the bank of initial measures, $l = \overline{1, L}$. The number ısures in each group is $M_l, m = \overline{1, M_l}$. As shown above, to analyze and control the pheric pollution in a city/region, it applies various criteria formalized using a complex of s aimed at calculating the economic damage, assessing the potential danger to coniferous and sulfur and nitrate compound transport.

Let us assume that the Q types of criteria used ($q = \overline{1,Q}$) allow an integrated assessment of the air basin pollution level in the city/region. Then, at stage 1, a matrix

$$E_l = (E_m^q) \tag{4.90}$$

is calculated for each group. This matrix consists of M_l lines and Q columns, where E_m^q is the effect of implementing the m-th action according to the q-th criterion. Each line of matrix E_l presents the "criterion vector" and the action m is effective in cases of at least a single element

$$E_m^q > 0 \tag{4.91}$$

The total number of efficient measures comprising the bank is expressed as

$$M = \sum_{l=1}^{L} M_l \tag{4.92}$$

Stage 2: Forming the permissible sets of measures

According to the possibilities of the initial bank, "permissible sets of measures" that present various types of air protection activity in the city/region can be formed for each l-th emitter group. A set is considered permissible if it includes no "alternative pair" of measures. Two measures are called alternative if they cannot be implemented simultaneously to reduce pollutant emissions, either for technical reasons or due to the inexpediency of such a combination. This situation frequently occurs, e.g. when two types of dust collectors of equal efficiency are used at a single source, or when a boiler house is converted to gaseous fuel at the same time that sulfur refining equipment is installed. The combined implementation of activities depends on a number of specific conditions and, in general, one fails to formalize the search for alternative pairs in a large set of air protection measures. Therefore, while formalizing the bank of initial actions, the table of alternatives is assumed for each group in the form of square symmetrical characteristic matrices $\left(\chi_l^{ij}\right)$ of dimension M_l

$$\chi_l^{ij} = \begin{cases} 1 & \text{if actions } i \text{ and } j \text{ can be realized together} \\ 0 & \text{if actions } i \text{ and } j \text{ are alternative} \end{cases} \tag{4.93}$$

Let $\chi_l^{ii} = 1$. It is necessary to consider alternative pairs while establishing permissible sets in order to provide practical efficiency of the analytical results. Let us fix a criterion $q^* = q$, $q = \overline{1,Q}$ (a corresponding column of the matrix E_l, $l = \overline{1,L}$. We distinguish the measures within the l-th group for which

$$E_m^{q^*} > 0, m = \overline{1, M_l^*} \tag{4.94}$$

Then, all permissible sets of measures could be obtained for the l-th group whose number, in the absence of alternative pairs, is equal to:

$$S_l = \sum_{i=1}^{M_l^*} \sum_{j=1}^{C_{M_l^*}^i} \prod_{(\xi,\eta)\in\Omega_j(M_l^*)} \chi_l^{\xi\eta} \tag{4.95}$$

where $C_{M_l^*}^i$ is the number of combinations of M_l^* - the number of measures that satisfy the requirements (4.94) for the group l for i. The $\Omega_j(M_l^*)$ is the set of pairs of indices (ξ,η) in the lexicographical j-th subset $(\nu_1,\nu_2,\ldots,\nu_i) : \nu_1 < \nu_2 < \cdots < \nu_i, 1 \le \nu_k \le M_l^*$. S_l is $2^{M_l^*} - 1$ if all the $\chi_l^{ij} = 0$ for any $i \neq j$. In the general case, $S_l \le 2^{M_l^*} - 1$.

Considerable values of M_l^* and a small number of alternative pairs S_l can become quite large; however, not all permissible sets are efficient. Therefore, each set successfully formed according to the formula is compared to those compiled earlier. One of the two sets is considered inefficient if, at higher or equal cost, it provides smaller effect for the criterial estimation.

The set having the above characteristics is saved and used in the further analysis; the one providing the smaller effect at higher or equal cost is always excluded from subsequent analysis. Thus, for each group l, a monotonic sequence of combined air protection measures is formed that provides increased effect at raised costs.

Let $Z_l = Z_l^{(1)} - Z_l^{(2)}$ be the effect of the measure of group l, where $Z_l^{(1)}$ is a criteria estimation before the measure is used and $Z_l^{(2)}$ is the effect after. To describe these sequences, we introduce the functions

$$Z_l = g_l(X_l), l = \overline{1, L} \tag{4.96}$$

where X_l denotes the costs of a relevant efficient set of measures and Z_l is the effect achieved at given costs in the group l.

The costs of air protection measures are of a discrete nature, i.e., a specific action requires a certain fixed amount of costs and, depending on the allocated funds, the activity is implemented either completely or not at all. At the same time, the effect of measures is nonlinerly related to the costs. Therefore, the "cost–effect" functions (4.96) for the group l are discrete, nonlinear, and assigned in the form of tables; in general, it is impossible to evaluate their mathematic parameters. Also, the number of cost levels N_l for the measures of the l-th group $\left(X_l = \{x_j\}_{j=1}^{N_l}\right)$ corresponding to the number of efficient permissible sets can be rather considerable, their sum amounting to several thousand variants. Thus, the further analysis of $N = \sum_{l=1}^{L} N_l$ permissible effective sets requires the use of specific optimization models.

Stage 3: Optimizing the distribution of costs of air protection measures

A special distribution model is meant to evaluate optimal sets of air protection measures in a city/region depending on the costs and type of criteria selected at Stage 2. (The set of permissible effective variants is used as initial information.) The obtained permissible effective sets are characterized by their alternative nature within each group $l = \overline{1, L}$. Therefore, at Stage 3, optimal sets are compiled by combining the measures referring to different groups.

The completely alternative nature N_l of effective sets within group l allows the presentation of cost distribution as a sequence of dynamic programming steps. While enabling the solution of discrete problems, such an approach specifies no strict requirements to mathematical properties of the functions Z_l.

The optimization model has the form

$$\sum_{l=1}^{L} Z_l = R(X_1, X_2, \ldots, X_L) \rightarrow \max \tag{4.97}$$

$$Z_l = g_l(X_l), l = \overline{1, L} \tag{4.98}$$

$$\sum_{l=1}^{L} X_l \leq K \tag{4.99}$$

$$X_l \geq 0, \qquad l = \overline{1, L} \tag{4.100}$$

where $X_1, X_2, \ldots, X_L$ are the costs of air protection measures carried out at the sources of the $1, 2, \ldots, L$ groups, respectively. The model maximizes the total effect of air protection measures within the allocated costs K. While realizing the model, dynamic programming produces a family of solutions (optimal sets), each corresponding to a certain level of costs not exceeding K. Thus, the relation (4.99) serves as the upper limit.

Since the multitude of permissible effective combinations (Stage 2) is discrete and finite (N), a complete optimal set can be compiled in which the costs K_M are maximum in respect to the possibilities of the initial measures bank. Substituting $K = K_M$ into the right-hand part of

inequality (4.99) would yield a complete optimal cost–effect function for the city/region obtained for the whole multitude of efficient variants.

The main principle of constructing a multi-step procedure to soive model (4.97)-(4.100) using dynamic programming consists of the following. Assuming that, at Stage 2, discrete values of costs are obtained within each group l for permissible effective sets:

$$V^{(l)} = V_n^{(l)}, \qquad n = \overline{1, N_l} \tag{4.101}$$

Let us introduce the sequence of steps $t = \overline{1, L-1}$ and determine the functions:

$$\begin{aligned} f_1(y_1) &= \max[g_1(X_1) + g_2(X_2)], \qquad y_1 \in U^{(1)}, \quad y_1 \le K \\ &\quad X_1 \in V^{(1)} \\ &\quad X_2 \in V^{(2)} \\ &\quad X_1 + X_2 \le K \end{aligned} \tag{4.102}$$

$$\begin{aligned} f_2(y_2) &= \max[f_1(y_1) + g_3(X_3)], \qquad y_2 \in U^{(2)} \\ &\quad y_1 \in U^{(1)} \\ &\quad X_3 \in V^{(3)} \\ &\quad y_1 + X_3 \le K \end{aligned} \tag{4.103}$$

$$\begin{aligned} f_t(y_t) &= \max[f_{t-1}(y_{t-1}) + g_t(X_t)], \qquad y_t \in U^{(t)} \\ &\quad y_{t-1} \in U^{(t-1)} \\ &\quad X_t \in V^{(t)} \\ &\quad y_{t-1} + X_t \le K \\ &\quad t > 2 \end{aligned} \tag{4.104}$$

where $U^{(t)}$ is the definition domain of argument y_t representing the sub-multitude $\bigcup_{i=1}^{t} V^{(i)}$, and $f_t(y_t)$ characterizes the maximum effect obtained from the distribution of costs K by $t+1$ groups and presents the optimal cost–effect function for these groups.

Recurrent correlation (4.105) is the operator of transition from step $t-1$ to step t.

Thus, this multi-step procedure presents the solution to the model (4.97)-(4.100) as a pair-wise combination of permissible effective sets referring to different groups $l = \overline{1, L}$. The process described is illustrated in Fig. 4.6.

Let us consider the multi-step computer procedure for solving the model (4.97)-(4.100).

I. Step $t = 1$. Calculation of total estimates

$$\left.\begin{aligned} v_{ij} &= v_i^{(1)} + v_j^{(2)} \\ Z_{ij} &= Z_i^{(1)} + Z_j^{(2)} \end{aligned}\right\} \qquad i = \overline{1, N_1}, \quad j = \overline{1, N_2} \tag{4.105}$$

For discrete values of costs and relevant effects (groups 1 and 2)

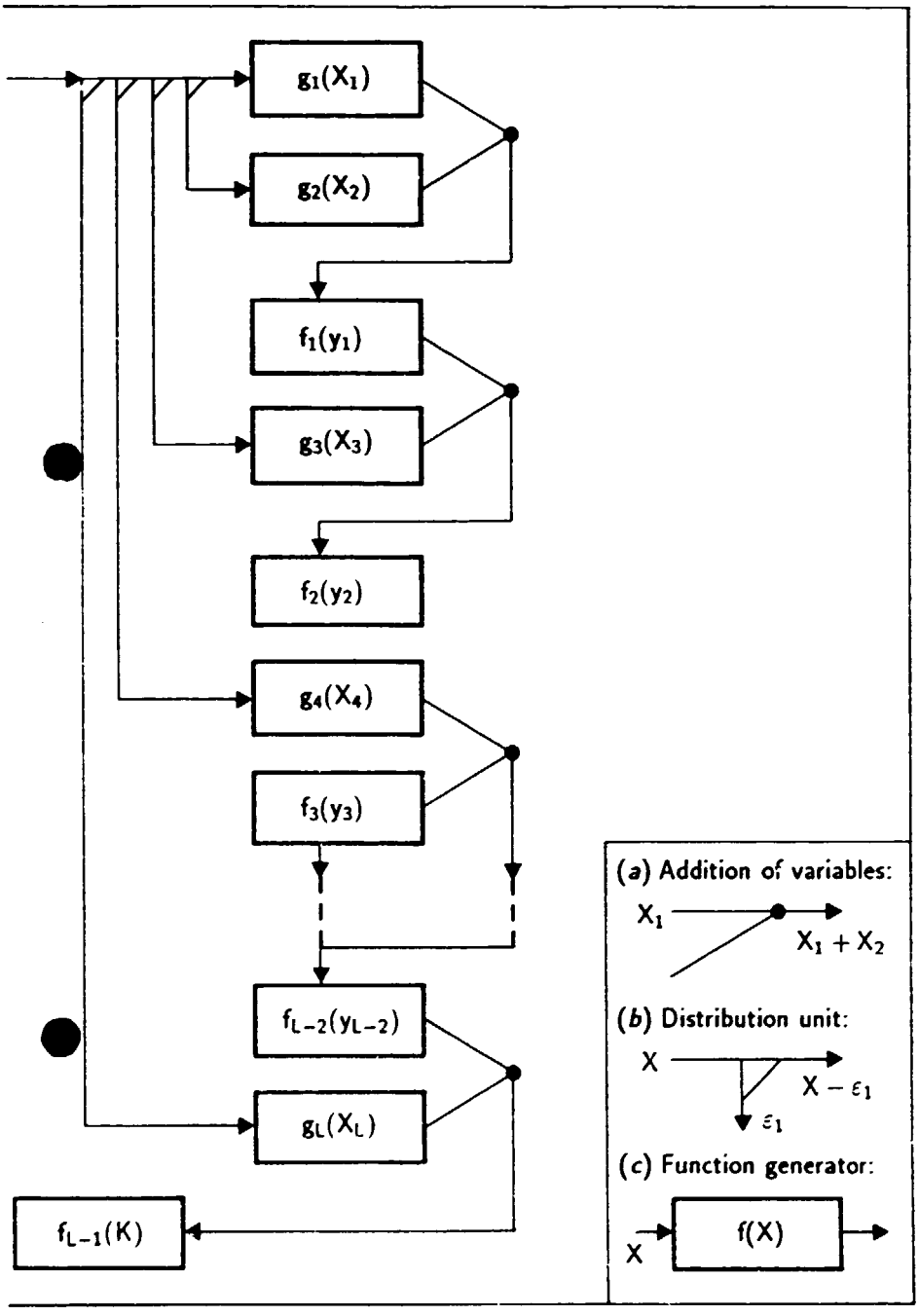
$$v_1^{(1)}, v_2^{(1)}, \ldots, v_{N_1}^{(1)}; \qquad v_1^{(2)}, v_2^{(2)}, \ldots, v_{N_2}^{(2)} \tag{4.106}$$

$$Z_1^{(1)}, Z_2^{(1)}, \ldots, Z_{N_1}^{(1)}; \qquad Z_1^{(2)}, Z_2^{(2)}, \ldots, Z_{N_2}^{(2)} \tag{4.107}$$

Construction of the vectors

$$\left.\begin{aligned} v &= \left(v_i^{(1)}, v_j^{(2)}, v_{ij}\right) = (v_r) \\ Z &= \left(Z_i^{(1)}, Z_j^{(2)}, Z_{ij}\right) = (Z_r) \end{aligned}\right\} \qquad r = \overline{1, N^*}, \quad N^* = N_1 + N_2 + N_1 \cdot N_2 \tag{4.108}$$

II. Arranging components of vector v according to the rising of costs.



Functional scheme of cost distribution ((a) addition of variables; (b) distribution unit; on generator).

III. Exclusion of inefficient estimates. If

$$r_2 > r_1 \wedge Z_{r_2} - Z_{r_1} \le \epsilon, \qquad r_1 = \overline{1, N^*}, \quad r_2 = \overline{1, N^*} \tag{4.109}$$

variant r_2 is considered inefficient as compared to r_1, and the r_2-th elements of vectors v and Z are excluded. The constant ϵ determines the accuracy of the model solution (the number of optimal cost–effect function components). Thus, ϵ helps to rarify (decrease the dimensionability of) vectors v and Z at each step.

V. Testing the limitations of (4.99). If

$$v_r > K, \qquad r = \overline{1, N^*} \tag{4.110}$$

the elements of vectors v and Z for the values $r, r+1, \ldots, N^*$ are excluded from further analysis.

V. Test: $t = L-1$. If the condition is fulfilled, we transfer to item VIII, otherwise to item VI.

I. Step $t+1$. At the t-th step we obtain the resulting cost vectors and the relevant effects

$$\left.\begin{aligned} y_t &= \left(y_i^{(t)}\right) \\ w_t &= f_t(y_t) = \left(w_i^{(t)}\right) \end{aligned}\right\} \qquad i = \overline{1, N_t^*} \tag{4.111}$$

Calculation of total estimates

$$\left.\begin{aligned} v_{ij} &= y_i^{(t)} + v_j^{(t+1)} \\ Z_{ij} &= w_i^{(t)} + Z_j^{(t+1)} \end{aligned}\right\} \qquad i = \overline{1, N_t^*}, \quad j = \overline{1, N_{t+1}} \tag{4.112}$$

where $v_j^{(t+1)}$ are components of vector v_{t+1} and $Z_j^{(t+1)} = g_{t+1}\left(v_j^{(t+1)}\right)$; then

$$\left.\begin{aligned} v &= \left(y_t^{(t)}, v_j^{(t+1)}, v_{ij}\right) = (v_r) \\ Z &= \left(w_i^{(t)}, Z_j^{(t+1)}, Z_{ij}\right) = (Z_r) \end{aligned}\right\} \qquad r = \overline{1, N^*}, \quad N^* = (N_t^* + N_{t+1}^* + N_t^* \cdot N_{t+1}^*) \tag{4.113}$$

. Transition to item II.

. Calculations complete. An optimal cost-effect function for the city/region is obtained.

The above process allows one to calculate the optimal cost-effect function and to determine numbers of the measures from the initial bank that form the set of optimal measures.

ge 4: Multicriteria analysis of optimal measure sets

set $\{R\}$ provides the initial data for the final selection of atmospheric protection strategies. set consists of vectors whose first two components are investment and annual costs, and the components are criterion estimations, corresponding to the discrete values of the functions lated in Stage 3.

et $R_i = \{R_i^h\}_{h=1}^{H}$ be one of these vectors ($H = Q+2$) and P_h be the priority of the criterion he criteria can be aggregated into intersecting sets. As examples, one can mention the ving:

the emission subset, whose components are compared by aggressive coefficients;

the economic damage subset, whose components are compared by monetary units;

the concentration indices subset, whose components are compared by the maximum allowable concentrations.

In this case the DM can assign priorities to the entire group but not to individual criteria.

While comparing the two atmospheric protection strategies R_i and R_j, one can consider the two values:

conformity index

$$c_{ij} = \frac{1}{p} \sum_{h:R_i^h \leq R_j^h} p_h \tag{4.114}$$

where $p = \sum_{h=1}^{H} p_h$;

unconformity index

$$D_{ij} = \begin{cases} 0 & \text{if } R_i^h \leq R_j^h (\forall h) \\ \frac{1}{\delta} \max\limits_{h:R_i^h \geq R_j^h} \left| \nu_h(R_i^h) - \nu_h(R_j^h) \right| & \text{otherwise} \end{cases} \tag{4.115}$$

where ν_h is a qualitative scale fir the criterion h, describing the changes in the criteria E preferences, and

$$\delta = \max_h \max_{i,j} \left| \nu_h(R_i^h) - \nu_h(R_j^h) \right| \tag{4.116}$$

Binary preference relations between R_j and R_i are determined by the threshold values of the conformity ϵ_1 and unconfirmed ϵ_2 $(0 \leq \epsilon_1, \epsilon_2 \leq 1)$ indices in the following way:

R_i is more preferable than R_j $(R_i \succ R_j)$ if $\epsilon_1 \leq C_{ij}$ and $\epsilon_2 \geq D_{ij}$.

This can only happen when:

- the criteria set (considering its preferences), where R_i is not worse than R_j, is representative and satisfies the threshold value ϵ_1;
- the other criteria estimations provide insufficient grounds, in accordance with the threshold ϵ_2, for excluding the assumption $R_i \succ R_j$.

The convocation process for the set $\{R\}$ consists of the exclusion sequence of some elements R and the definition of the nucleus $G(R, \epsilon_1, \epsilon_2)$ of the graph, of which the points are the elements R_i and the arrows $(R_i, R_j) \in G(R, \epsilon_1, \epsilon_2)$ if $R_i \succ R_j$.

The nucleus, $\mathcal{K}$, is a subset with the following properties:

- external consistency, meaning that for each element R_j excluded, there is at least one element R_i that is preferable to R_j $(R_i \succ R_j)$;
- internal consistency, meaning that there is no element left that is nondominated by any other element $R_l \in \mathcal{K}$ left.

If there are contours in $G(R, \epsilon_1, \epsilon_2)$, then the contour $\mathcal{L} \subset G(R, \epsilon_1, \epsilon_2)$ is excluded by the procedure if $\exists R_i \notin \mathcal{L}$ where $R_i \succ R_j$ and $R_j \in \mathcal{L}$. The contour elements are left for subsequent analysis.

Therefore the nucleus $\mathcal{K} \subset G(R, \epsilon_1, \epsilon_2)$ presents the information needed by the DM to choose the most efficient atmospheric protection strategies.

5 Conclusion

The IPAC system integrates several mathematical models from a variety of disciplines and trade-offs between accurateness of calculation and speed of PC runs. It is known that some models (e.g. transfer models in atmospheric physics) require significant increases in speed – up to the level of "supercomputing" – in order to increase accuracy. However, the accuracy and correctness of other models used in similar systems are left incomparable to transfer models.

In general it is possible to improve (or even replace with newer ones) each model used within the framework of the system. However, in so doing one should be sure to have a thorough understanding of the actual application needs and consequences.

The authors will continue the development of the system and new versions of the software. Comments and feedback are welcomed.

6 References

Air Pollution: Assessment Methodology and Modeling. 1982. NATO - Challenges of Modern Society Series: Vol. 1. Plenum Press.

Approximate Economic Damage Estimations of Air Pollution. 1986. Temporary methodology of calculations of environment protection activities' economic effectiveness and of assessment of economic damage caused by environmental pollution. Moscow: Economica. In Russian.

Awad, A. and T. Veziroglu. 1984. Hydrogen versus synthetic fossil fuels. Int. J. of Hydrogen Energy. 9(5):355–366.

Ben-chieh, Leu and Eden Siu-hung Yu. Air Pollution Damage Functions and Regional Damage Estimates. The University of Oklahoma, Technomic Publishing Co., Inc., USA.

Beryland, M.E. 1985. Air Pollution Predicting and Control. Leningrad: Hydromet. In Russian.

Burshtein, I.M. 1968. Dynamical Programming in Planning. Moscow: Economica. In Russian.

Cheng, L., E. Peake, D. Rogers, and A. Davis. 1986. Oxidation of nitric oxide controlled by turbulent mixing in plumes from oil sands extraction plants. Atm. Env. 20(9):1697–1703.

Climatic Characteristics of Air Pollution Transport in the Atmosphere. 1983. Leningrad: Hydromet. In Russian.

Cock, A., and I.S. Fletcher. 1988. Major factors influencing gas phase chemistry in power plant plumes during long-range transport. Atm. Env. 22(4):663–676.

Derwent, R.G. 1987. Treating uncertainty in models of the atmospheric chemistry of nitrogen compounds. Atm. Env. 21(6):1445–1459.

Ecological Advantages of Natural Gas over other Fossil Fuels. In: The Methane Age, edited by Lee, T.H., H.R. Linden, D.H. Dreyfus, and T. Vasko. IIASA & Kluwer Academic Publishers. 1988. pp. 155–161.

Eliassen, A. 1980. A review of long-range transport modeling. App.met. 19(3):231–240.

Galperin, M.V. 1985. Statistical fluctuation of atmosphere pollutants deposition rates and their influence on transport processes. Proceedings of Institute of Applied Geophysics 62. In Russian.

Fisher, B. 1983. A review of the processes and models of long-range transport of air pollutants. Atm. Env. 17(10):1805–1515.

Forrest, J., R.W. Garber, L. Newman. 1981. Conversion rates in power plant plumes based on filter pack data: the coal-fired Cumberland plume. Atm. Env. 15:2273–2282.

Gillilani, N.V. 1983. Gas-to-particle conversion of sulfur in power plant plumes - the parameterization of plume-cloud interactions. Atm. Env. 17:1753–1763.

Henry R. 1984. Review of receptor model fundamentals. Atm. Env. 18(11):1507–1515.

Hov, O., A. Eliassen, T. Iversen, and D. Simpson. 1988 EMEP NO_x-model: formulation and some results. Workshop on modeling transformation process and transport of air pollution with special reference to nitrogen oxides. Potsdam. pp. 105–109.

Izrael, Yu.A. 1983. Acid rains. Leningrad: Hydromet. In Russian.

Izrael, Yu.A., I.M. Nazarov, A.Yu. Pressman, F.Yu. Rovinsky, A.G. Ryaboshapko, and L.M. Filipova. 1989. Acid Rains. Leningrad. Gidrometeoizdat.

Janssen, L.H. J.H. van Wekeren, H. van Duuren, and A.J. Elishout. 1988. A classification of NO oxidation rates in power plumes based on atmospheric conditions. Atm. Env. 22(1):43–53.

Lee, N. 1985. Three dimensional analytical models. Atm. Env. 19(12):1951–1957.

Marchuk, A.I. 1982. Role of mathematical modeling in environmental problems. Moscow: Nauka. In Russian.

Mendelsohn, R. 1980. An economic analysis of air pollution from coal-fired plants. J. of Env. Econom. and Management. 7:30–43.

New Airclimatic Reference Book on Marginal Stratum of Atmosphere over the Territory of the USSR. 1987. Leningrad: Hydromet. Nos. 5,8.

Physico-Chemical Behavior of Atmospheric Pollutants. Proceedings of the Third European Symposium held in Varese. D. Reidel Publishing Company, 1984. 666 pp.

Recommendations on Source Conjunction in Preparation of Data for Computer calculation of Air Pollution. 1983. Proceedings of State Geophysical Observatory. In Russian.

Renner, E., V. Ratzlaff, and W. Rolle. 1985. A Lagrangian multi-level model of transport, transformation and deposition of atmospheric sulfur dioxide and sulfate. Atm. Env. 19(11):1351–1359.

Ryaloshapko, A.G. 1983. Atmospheric cycles of sulfur. Global biochemical cycle of sulfur and human activity. Moscow: Nauka. In Russian.

Ryaloshapko, A.G. 1988. Mathematical modelling of chemical transformation processes during long-range atmospheric transport. Workshop on modellilng transformation processes and transport of air pollution with special reference to nitrogen oxides. Potsdam, pp. 68–72.

Schmel, C.A. 1980. Particle and gas dry deposition: a review. Atm. Env. 14:983–1011.

Van Egmont D., and H. Kessenboom. 1983. Mesoscale air pollution dispersion models. Atm. Env. 17(2):257–274.

Zavodsky, D. 1988. Long-range transport of nitrogen oxides in central Europe. Workshop on modellilng transformation processes and transport of air pollution with special reference to nitrogen oxides. Potsdam, pp. 60–62.