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GLOBAL DISCRETIZATION IN ENVIRONMENTAL IMPACT ASSESSMENT STUDIES

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Abstract. The paper presents a computer oriented methodology for an efficient assessment of the environmental impact from the operation of facilities causing air born type of pollution. The efficiency regards mainly two factors: algorithmic speed and size of memory requirements. Existing methods, as a rule, failed to perform an efficient assessment over the full range of urban and meteorological data for the following main reasons: the treatment of urban and meteorological data as continuous variables and the application of the basic pollutants distribution gaussian type of model, which is an extremely complex one, over a continuous domain of data. The proposed methodology is based upon a discretization, conforming with the usually applied accuracy, of the continuous domain of meteorological, spatial (urban) and pollutants concentration data. The introduced discretization is capable of reducing the computational effort by thousands of times. This significant reduction enables for the development of locational methods covering several hundreds of candidate sites as well as the development of collective pollution impact assessment indices at a regional level. The latter information can be used in the process of location of industrial areas and parks.

The models and the solution methodology introduced in this paper were applied for a long range impact assessment that covered all communes of Belgium. The pilot unit was an incineration plant, planned to be established in Brussels Region, with emitted thermal flow of 5 (MW), with an emitted pollution mass of 1 kg per hour and a stack height equal to 69m.

Keywords: Environmental Impact Assessment, Air Born Pollution, Discretization

1. INTRODUCTION

1.1 Aims of the study

The present state of affairs regarding environmental management and planning, especially the environmental impact assessments for air polluting activities, is characterized by serious deadlocks. On the other hand, the rapidly increasing awareness of the international community, especially in Western Europe and North America, has created a positive environment in the context of which problems could be more easily recognized, appreciated and understood and efficient, but costly sometimes, solution methods can be more easily accepted by the society.

The main problems regarding the environmental impact assessment activities are:

1. *The enormous waste of human and capital resources.*

2. *The negative impact on the quality of life*

Notice that the recent trends in the corresponding legislative framework widen the spektrum of (polluting) activities that are obliged to submit to the local or central administration appropriate environmental impact studies. The rapidly increasing demand for such studies, both in the private as well as in the public sector, created a positive environment for the emergence of a plethora of consultancy firms specialized in impact assessment studies, the quality of their products being some times questionable. On the other hand, a plethora of such studies is performed in the context of the same climatic conditions or urban structures with apparently extensive duplication of efforts

1.2 The social impact

The following factors could contribute negatively to the quality of impact studies and the interpretation of their results with an apparent negative social impact (Karkazis 1993a):

1. *Serious gaps in the existing legislative framework*

2. *Lack of interdisciplinarity in the synthesis of the relative decision making hierarchy and the scientific teams*

3. *Lack of appropriate communication channels among scientific/groups and between these groups and the decision makers*

4. *Lack of concrete evidence on the impact of the (atmospheric) pollution on the quality of life and in particular the public health.*

5. *Lack of appropriate scientific and ethical principles that will control all stages of impact assessment studies and their interpretation.*

- *Through the interactions (somє times frictional) between national ppans of different countries the necessity will arise to look at and regulate the problems at an international level.*

- *There is already a plethora of signs that supernational entities, like EU, are moving fast and decisively towards this direction.*

1.4 The principles applied in this study

The principles, scientific and ethical, applied in this study are:

- *The principle of **globality***
- *The principle of **relativity***
- *The principle of **social sensitivity***

The first principle was applied both at the level of modelling (spatial and socio-economic range) as well as at the level of **interdisciplinarity**. We have extended the spatial/urbanistic range of the assessment to practically all areas that can receive pollution loads capable of creating even a low socio-economic impacts. We have also extended the spektrum of assessment measures and their structure to include beyond the *max types* (which record the maximum pollution concentration), average types (that record the average pollution loads received by individuals at a communal, regional or national level) as well as economic types (trying to capture a wide spektrum of possible effects on the economy as a whole. We have also introduced the concept of **non_linearity** in the relationship between pollution load and effects on the health and between total (summarized) public health burden and the corresponding financial burden caused at a communal, regional or national level. On the other hand, having realized the complex interactions of various disciplines involved in the problem (mainly of physics/mathematics, locational analysis, and environmental management) we were involved in extended contacts with experts from these fields, and especially with experts on atmospheric dispersion in VITO, Mol.

It is worthwhile mentioning at this point that the last 10-15 years in Locational Analysis literature and forums increasing criticism is recorded, mainly calling for adjustment of models/methods to the reality and not the reverse which is sometimes the practice. It is indicative the paradox that climatic conditions had been systematicly ignored for many years or inadequately or distorted included in the locational models.

The second principle in combination with the theoretical concepts of descritization, reduced large domains of continuous spatial and meteorological data to an extremely narrow discretized set of data capable of being installed in any kind of p.c. As an example, the required in many applications accuracy (resolution) of spatial data is not more than 250 m whereas the accuracy of existing meteorological data (eg wind velocity) is not going below one decimal point. By applying the notion of relativity in this context, significant readjustments in the modelling and processing phase are required so as not to allow computational efforts to be wasted trying to achieve redundant levels of accuracy.

The third principle was expressed during the study with introduction of measuring and interpretation concepts capable of recording among other values **worst case possibilities** for the public health and the economy.

Finally, the introduced modelsmethodology make possible the assessment at a regional or national level of **environmental and economic equity policies**.

In order the legislation framework to be effective it should be equipped with the following regulative powers and principles. (Karkazis 1997, 1998):

i. With regulatory mechanisms that will cover the phases of data collection and processing putting appropriate standards on the quality of data and the trustworthiness of data sources.

ii. With validating mechanisms for the phases of modelling and processing, and harmonization mechanisms of standards and methods when applications cover more than one country.

iii. With mechanisms regulating the size, resources and interdisciplinarity of assessment teams according to the type and size of the assessment

iv. To regulate the estimating mechanisms of pollution effects and introduce ethicly and socially sound principles that will govern the interpretation of assessment.

With respect to the last issue, efforts should be made so as long range impact measures are present in the objectives of assessment models, measures that will be capable of covering spatially all affected populations and capturing the widest possible range of possible impacts of pollution to the public. It is worthwhile mentioning at this point that most assessments are based on measures evaluating extreme pollutants concentration during very short term periods of time in "shock type" pollution incidents which take place as a rule inside a zone of 10-15 km from the polluting unit. As we will show later high pollution loads can recorded for as far as 100 km from the unit capable of affecting tens of thousands of sguare kilometers and millions of inhabitants. On the other hand, the interpretation phase should be as much as possible governed by the ethical principle of "not transferring to the public the negative impact resulting from the lack of knowledge regarding the above issues or the lack of concrete evidence.

1.3 The significance of the study and the expected chain effects

The development of low-cost, long-range and high-quality environmental impact assessment moodels/methodologies could decisively help in resolving many of the above mentioned problems directly or synergeticly.

The introduced theoretical concepts of **spatial and computational descritization** can under certain conditions ("flatness" of the basic functions) become powerful tools in the modelling and evaluation phases. Indeed in the case of our study, spatial and computational discretized structures appropriately implanted in the impact assessment process, can enable long range assessments practically reaching hundreds of kilometers with extremely low cost: computational time not exceeding 7-10 hours and memory requirements not exceeding 155KB.

The synergetic process that is expected to be developed as a result of drasticly lowering the assessment cost and upgrading assessment output quality could be characterized by the following phases:

- *The reduction of cost requirements is expected to ignite, through profit considerations for the private sector and through social considerations for the local authorities, the interest of both sides to undertake large range assessment activities.*

- *Through the interactions of local authorities and private sector with the central government the latter will develop an interest to exploit such approaches to promote planning and regulative policies regarding the polluting (mainly industrial activity) at a national level.*

2. AIRBORNE POLLUTION SPREAD MODELLING: A LITERATURE REVIEW

2.1 Governmental regulation: a narrow-minded legislative framework

A lot of incentives, tools and policies for regional development are not functioning properly due, mainly, to the absence of coordination between private and public initiatives, serious deficiencies in the corresponding legislative framework and above all due to the great problems associated with the process of adjustment of regional planning policies, methodologies and models to a continuously and rapidly changing international socio-economic environment (a synopsis of the above problems can be found in Karkazis, 1993b). Of special interest to the present work are the problems related mainly to the spatial organization of industrial activity with environmental criteria

Karkazis (1993b) distinguishes the following two serious gaps in the legislative framework regarding the protection of environment from organized industrial activity:

> *"1. Lack of legislation introducing upper limits for the total emission of pollutants in I.A.'s. The legislation introducing upper limits to the emission of certain pollutants from individual stacks is not a sufficient measure for areas accommodating large industrial activity where the cumulative pollutants' emission rates may exceed the safety limits and create serious hazards to the population and its environment. The process of specifying cumulative upper limits should take into account the following basic factors: the morphology of the ground, the meteorological conditions prevailing in the area under consideration and the distribution of population in it.*
>
> *2. Lack of 'internal plans' for the location of polluting units inside an I.A., mainly concerning environmental criteria".*

2.2 Location and stack height: the determining factors

The location of continuously emitting polluting units and their stack heights are the determining factors through which their impact on the environment could be controlled and the appropriate (just and economically effective) distribution of environmental cost can be achieved.

Karkazis (1988) analysed the latter problem with reference to the I.A. of Thessaloniki and proposed an internal organization plan. His main conclusions were:

> *"1. The variation of the total pollution load of the neighboring urban sites as a result of relocations of the polluting unit inside the I.A. is very significant. Note at this point that the I.A. of Thessaloniki has roughly the shape of a rectangular 2.5 km × 1.5 km (...) In particular, the variation of the maximum to the minimum value of the total pollution load is approximately 1000.*
>
> *2. For the prevailing meteorological conditions and the existing distribution of urban sites around the I.A. an average stack height of 20 m (equivalent stack height 40 m) minimizes the total pollution load. For stack heights greater than 20 m an increment of the total pollution load is recorded".*

2.3 Modelling the impact on the environment

Pasquil (1961) and Turner (1970) gave an in-depth analysis of the mechanism with which airborne pollution is spread. In the presence of a single wind the basic parameters governing pollution spread are:

- High wind speeds, causing enlargement of the pollution plume and the subsequent reduction of the pollutants' concentration in it. Low wind speeds cause the reverse effect.

The pollutants' plume exhibits some very interesting characteristics that should be closely viewed when deriving corresponding pollution spread models (Strom, 1976). These are:

- Pollution spread is confined to a narrow angle (approximately 20-25^0) along wind direction.
- Pollutants are carried a long distance along the wind direction (frequently 10-30 km). As an example, for the meteorological conditions prevailing in Thessaloniki, Northern Greece, the maximum concentration of pollutants, corresponding to an equivalent stack height f 100m, appears between 12,5km and 15km (depending on the wind direction) from the site of polluting unit. Furthermore, pollutants' concentration remains relatively high (within 30% of the maximum value) as far as 25km-30km from the polluting unit.

3. THE MODELS AND PROCESSING METHODS INTRODUCED

3.1 The spatial framework

The target here was to find an appropriate discretized representation of the spatial distribution of population in Belgium. The final choice of the representative structure was the result of trade-off considerations between following factors:

- *The available data*
- *The required accuracy*
- *The efficient control of accuracy*
- *The minimization of the processing (computational effort).*

The available data contained information regarding the population and the border topography for 586 communes in Belgium with a poppulation totalling to 10,095,209 inhabitants (see appendix 1 for maps).

The format of available data at the level of a commune (see appendix 3) was:

NAME OF COMMUNE - CODE OF COMMUNE - POPULATION OF THE COMMUNE

(these are stored in an attached file named BEL-POP.DAT, see also appendix 3.1)

NUMBER OF BORDER NODES(n)

x1 y1
x2 y2
...
xn yn

where xi,yi are the x- and y-coordinates in meters of point Pi in a polygonal representation of the communes border (figure 1)

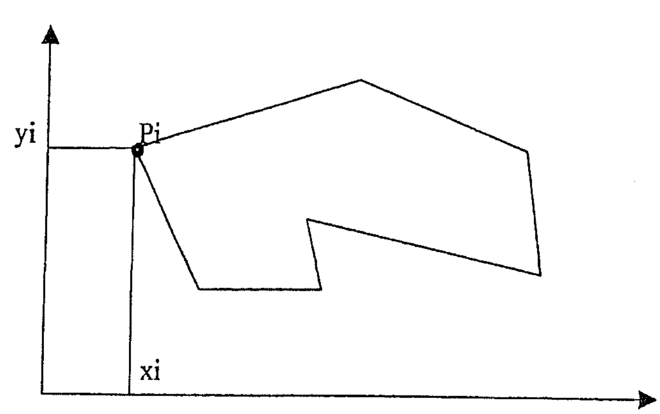


FIGURE 1. The spatial communal structure

In the majority of applications the resolution of spatial representation is not going below 250 m. Furthermore, in the absence of more detailed spatial data, going below 250 m would have no real representative value. So a resolution of 250 m was taken as the best compromise.

As far as the type of spatial representation is concerned, we have selected a rectangular system of planar grid points because it can provide through its ortho-canonical form efficient control of accuracy of the results and efficient processing of grid points (see grid assignment algorithm).

The adopted spatial discretized structure is shown in figure 2.

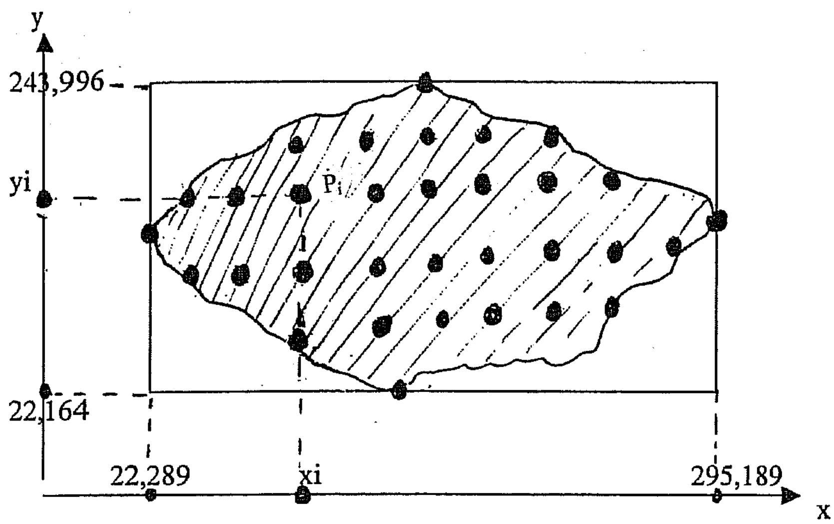


FIGURE 2. The discretization of the spatial domain

Note that inside this grid structure the coordinates of Belgium grid points varied as follows:

Min x-coordinate= 22,289 (meters) Max x-coordinate=295,189
Min y-coordinate=22,164 Max y-coordinate=243,196

In the above context the number of grid points representing Belgium is approximately 640,000

As far as communes are concerned, the spatial system of grid points it represents them constitutes a subset of the national grid point system (see figure 3). On the other hand, the population p(R) of a grid point of a region R is taken to be:

$$p(R) = s(R) / n(R) \tag{3.1}$$

where s(R) represents the population of region R and n(R) the number of grid points in it. The above population assignment is based on the fact to the distribution of grid points is homogeneous.

An algorithmicly difficult problem that arises at this level regards the determination of the following values:

- *The number of points in a given region R*
- *The region which a given grid point belongs to*

3.2 The GRID ASSIGNMENT algorithm

The ortho-canonical spatial structure offered the means of constructing an efficient algorithm to determine the above values. Note at this point that the algorithmic complexity of the problem increases drasticly when the region is non-convex as it is the case with the present study.

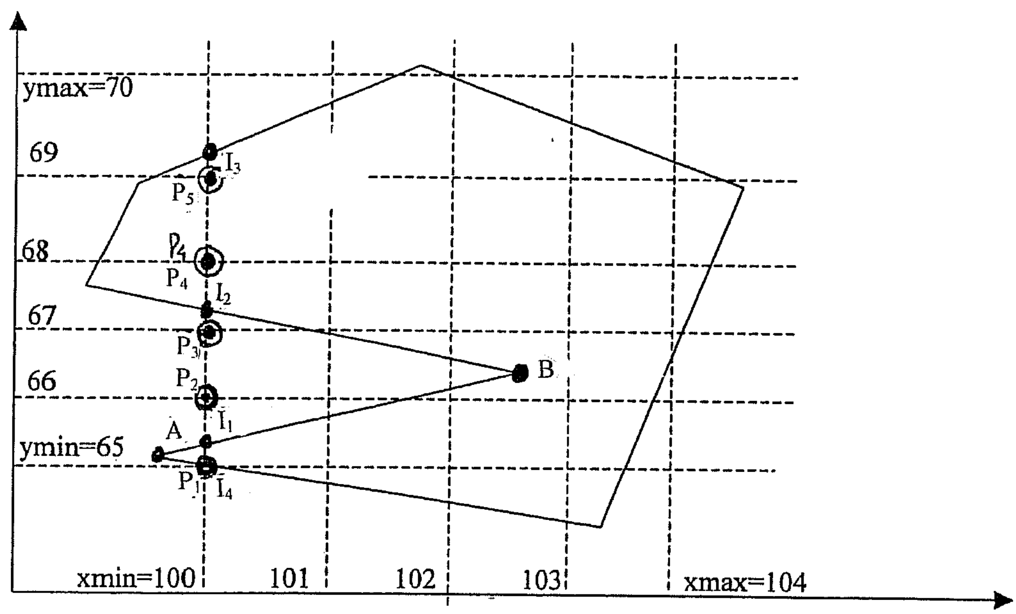


FIGURE 3.The GRID-ASSIGNMENT algorithm

The following well-known non-convexity result is also applied in the proposed algorithm called thereon GRID-ASSIGNMENT algorithm.

RESULT 3.1. If A= (A1,A2,A3...An) is the set of intersection points of a straight line with a non_convex polygon (region) R then n is even and the interval [Ak,Ak+1] k=odd (1,3,..) is a subset of R.

The algorithm

Step 1. Determine the end_most and right-most grid point of the region R. Let xl and xr be their x-coordinates resp.

and x1,x2,...,xn the non-co...nciding projections (in ascending order) of grid points of the region R: xl <= x1 < x2 <..

xn <= xr.

Step 2. For each xi determine the set of intersection points with the the perimeter of the region of the 'vertical' straight line passing through xi.

If vertical line passes through a vertex of the region then duplicate intersection. Put in ascending order the elements of the above set and get ordered set Vi={vi1,vi2, ... ,vik}. Duplication of vertex intersections quarrantees that intersection set contains an even number of elements.

Step 3. For each set Vi repeat the following:

Consider segments segij=(vij,vij+1) j=1,2,..,k/2 of the vertical line corresponding to xi (from the above these segments coincide with the intersection of the vertical line with the region) and for each segment segij determine the y-coordinates, say yijl l=1,2,...,r, of the grid point(s) belonging to it.

Step 4: Assignment. For each i=1,2,...,n, for each j=1,2,..,k and for each l=1,2,..., r assign grid point (xi,yijl) to region R

The algorithm compared very favourably with established algorithms in the literature by reducing the computational time by 50-100 times

3.3 The BIN-SORTING algorithm

The GRID ASSIGNMENT algorithm requires an ordered set of intersections as input. This means that the intersections of each vertical line xith the arcs of the region should be first calculated and then put in an increasing order. It is apparent that this process will be repeated a very big number of times (actually as many times as the number of grid points in Belgium which is approximately 640,000).

The above requirement together with other computational requirements during the study made necessary the development of a ver fast ordering algorithm.

The basic idea behind the proposed sorting method is the exploitation of the invested order in the digital representation of numbers in computers.To give an example, consider number a number x=20.678. The truncation routine performed by a computer can determine very efficiently in terms of time the interval in which these numbers lie. Thus, if we choose to place them in the intervals: I1= [20,21) and I2= [21,22)... then this does not require further computational effort (of comparison and sorting type) beyond the one required by the truncation routine: k=trunc(x-20)+1 gives the interval in which x belongs to.

The following result is a straightforward application of the

RESULT 3.2. Consider the infinite series of intervals: 1st int.:[A1,A2), 2nd int: [A2,A3),...nth int: [An,An+1)..... where Ai are reals such that Ai < Ai+1, Ai+1-Ai=d i=1,2,..., and a real number x. Then, x belongs to the interval k = trunc((x-A1)/d)+1.

The algorithm

Step 1. Determine the series of intervals of Result 3.2 called thereon "bins" (their numer and size influence the speed of sorting) and a series of real numbers xi i=1,2,3,.... Requiring ordering.

Step 2. Using step result 3.2 distribute them to the "bins"

Step 3. Apply any already established ordering process to order the numbers located at each "bib".

The algorithm exhibited in the tested cases sub-linear performance, outperforming for the data tested the existing sorting methods.

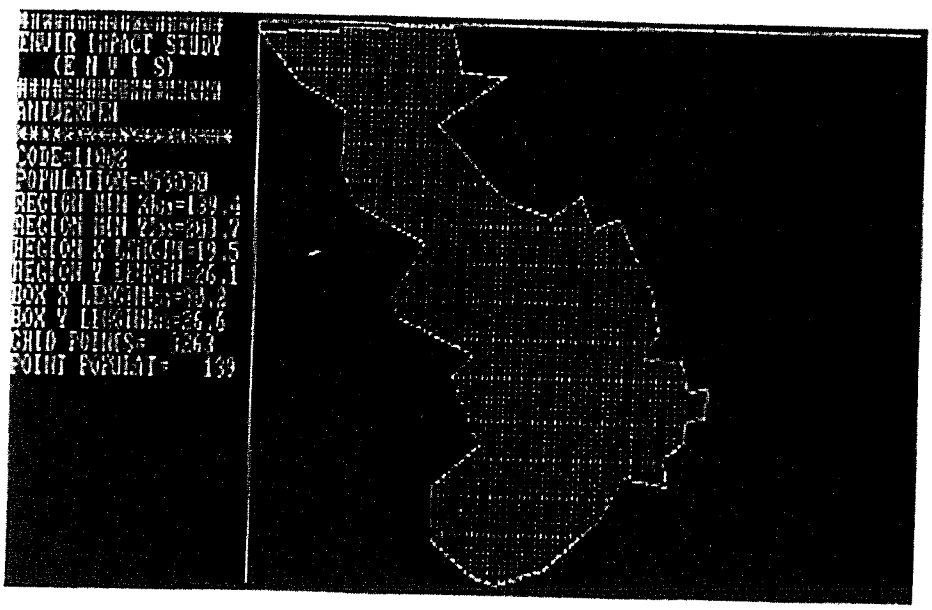


FIGURE 4. Grid points assignment

3.4 The environmental framework

To simplify the environmental impact analysis that will be based on the IFDM dispersion model (see Appendix 2) we re-write formuli (2.1), (2.2) and (2.3) so as to take into account the range and interdependence of all meteorological parameters employed in the model:

$$APC(U,P) = \sum_{i=1}^{360^\circ} F(di) \sum_{s,u} F(s\ u)\ Cisu(U,P) \tag{3.1}$$

$$TPL(U, \mathbf{R}) = \sum_{P \in \mathbf{R}} W(P)\ APC(U,P) \tag{3.2}$$

Cisu(U,P) gives the pollutants concentration (in mg/m^3) at point P due to a polluting unit emitting at point U under the following meteorological conditions: wind direction di, stability class si and wind speed ui (in m/sec).These values are considered to be taken at time Ti where the sequence Ti i=1,2,...k defines a series of equally distant time instances covering a period of time T. APC(U,P) gives the average pollution load (average concentration) at point P during the period of time T (eg. meteorological values could be taken at an hourly basis covering a period of one year). F(di) gives the frequency of wind direction di (usually di is measured in degrees ranging from 1^0 to 360^0) and F(si,ui) the frequency of the meteorological pair (stability si, speed ui) during the period T. Note that the separation of parameter di from the pair (si,ui) serves only algorithmic purposes. Usually, at each time instant all three meteorological parameters are evaluated. Finally W(P) represents the population assigned to point P and **R** a geographical region (in our case a commune or Belgium itself).

Theoretical analysis and numerical experience suggests that the function C exhibits for all combinations of meteorological parameter values strongly "flat"areas a prerequisit for the application of efficient discretization schemes for the spatial distribution of its values. In order to further analyse the possibilities of efficient discretization we performed a complete enumeration of its values for a wide range of combinations of meteological parameter values: stability class ranging from 1 to 7 and wind speed ranging from 0.1 to 10 with step 0.1 m/sec (equivalently from practically zero speed per hour to 36 km per hour). The technical characteristics of the polluting unit employed were: emitted pollution mass = 1kg/hour, emmitted thermal flow = 5 (MW) and stack height = 69 meters. These characteristics are typical of small to medium polluting units employing efficient pollution filtering.

Note that the range of meteorological parameter values considered in the complete enumeration cover almost all the spektrum of normal meteorological conditions, except the extreme wind speeds, with an accuracy compatible with the accuracy of existing meteorological data.

As far as the accuracy of pollutants concentration is concerned we considered values below 0.1 mg/m as practically zero, consequently employing for the descritization performed an accuracy of 0.1 mg/m^3, that is we discretized the spatial distributionthe of

C values by recording them (at points on the plane) whenever they were becoming multiples of 0.1 mg/m^3. The above descritization is compatible with the existing international standards and the employed internationally accuracy of C values which is 0.1 mg/m^3. Notice at this point that official USA standards are 150mg/m^3 whereas proposals of the British Panel of Experts is 50 mg/m^3

The complete enumeration that led to the discretization of C values was performed as follows (see figure 5):

Measurements along the x-axis were taken every 25 meters starting from zero distance. Whenever a multiple of 0.1 mg/m was recorded on the x-axis with an accuracy of 0.01 (actually the 25 meters step secured this accuracy) the value and the coordinates of the site, say (x,0), were recorded and a vertical search (a search along a straight line vertical to the x-axis at point x) was performed with the same way. Due to the symmetry of function C along the x-axis only the positive part of the vertical axis was scanned.

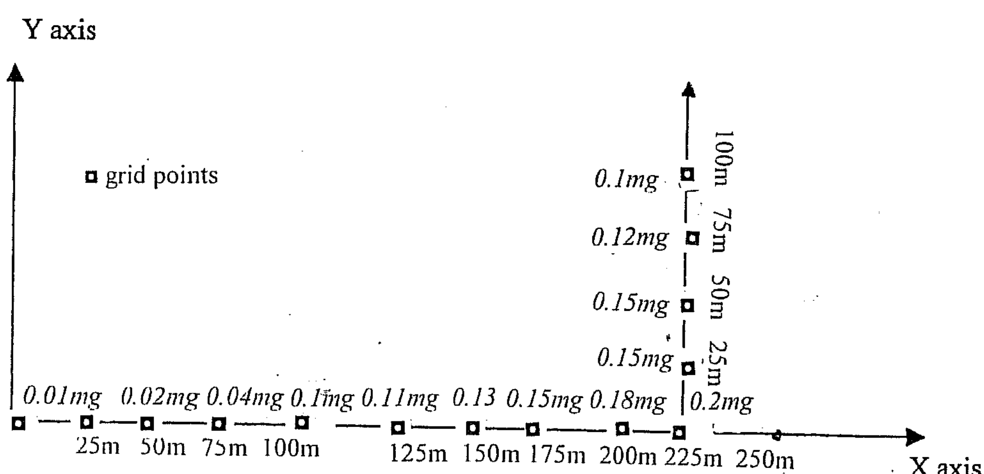


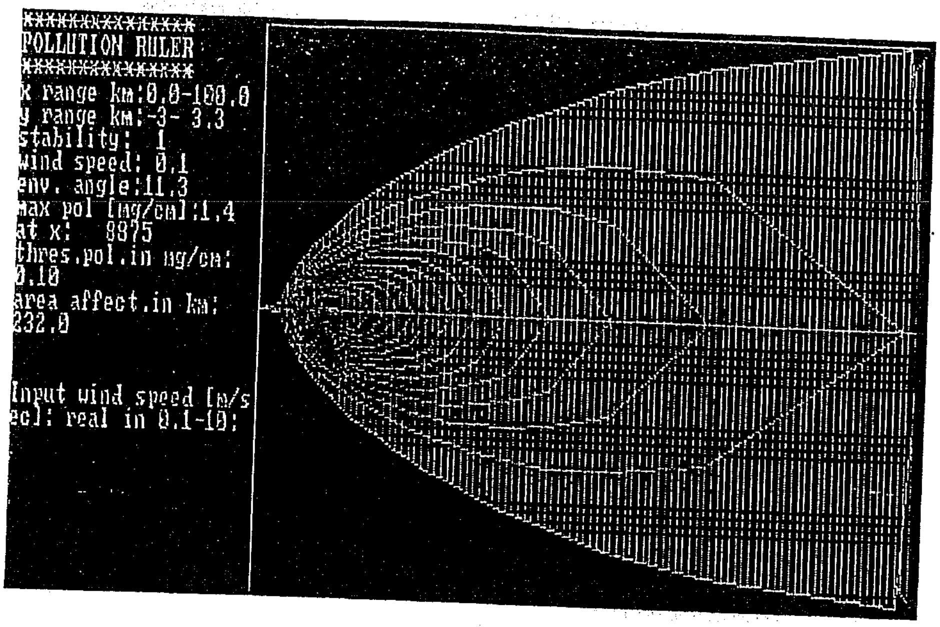
FIGURE 5. The evaluation of the pollutants concentration discretized values

From thereon, all planar points at which multiples of 0.1 mg/m^3 concentration was recorded will be called (pollution) *grid points.*

Next, we constructed (using linear interpolation) the *iso-polluting curves* by uniting with straight line segments all grid ponts characterized by the same pollutants conentration. The resulting structure (see figure 6) consists of a system of trapezia, called thereon *grid trapezia.*

RESULT 3.3. Consider a convex polygon located strictly at the one side of the x-axis. Then, the function C takes its maximum (minimum) value at one of the vertices of the convex polygon

Proof. (see Karkazis and Papadimitriou (1992)).



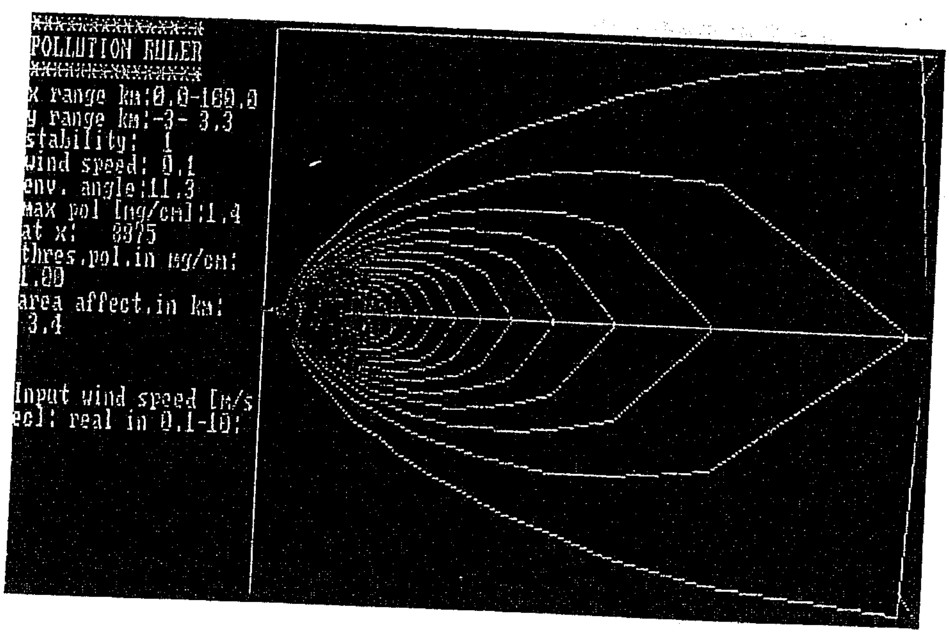


FIGURE 6. Pollution Rulers

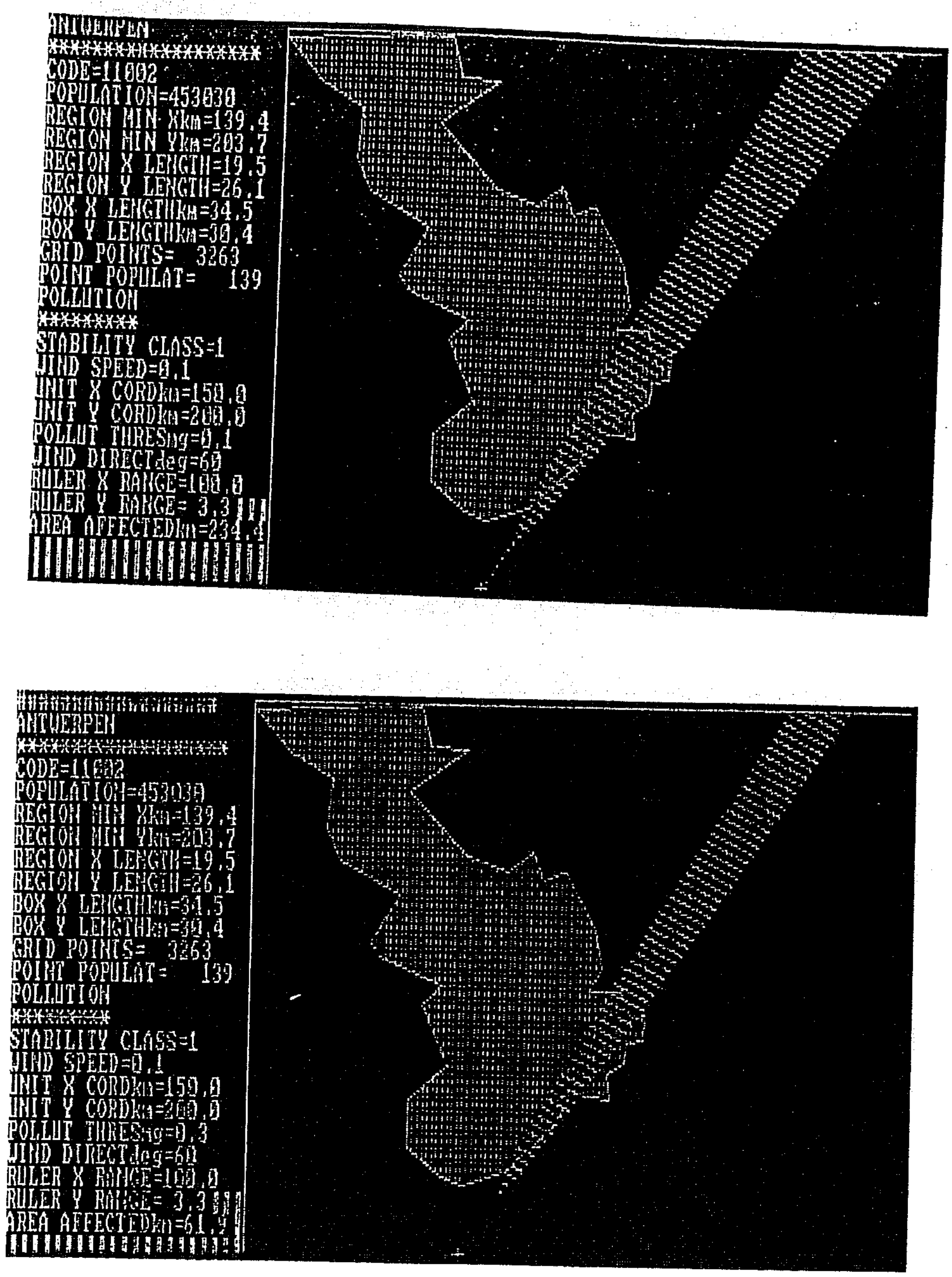


FIGURE 7. The pollution spatial impact evaluation

This structure in combination with Result 3.3 allows for the construction of a simple but very efficient algorithm for evaluating the concentration at any planar pont P(x,y). The evaluation of the concentration reduces to locating the trapezium P belongs to which is a sraigthforward process.The maximum concentration on this trapezium according to Result 3.4 (see below) coincides with the concentration along its lower iso-polluting side. This concentration (and not other average interpolation measures) for reasons of social sensitivity is taken as the (approximate) concentration at point P. Since the system of grid trapezia allows not only algebraicly but also visually (through the graphical representation given by the attached codes) for a simple and efficient evaluation of C values we called this system of trapezia **pollution ruler.**

RESULT 3.4. The maximum deviation of the values of function C on a grid trapezium is equal to 0.1 whereas its maximim (minimum) value is recorded at one of its vertices
Proof. It is an immediate consequence of Result 3.3 and the way grid trapezia were constructed.

The above descritization proved to be extremely powerful. for all combinations of s and u parameters tested.

Analysis of Pollution Rulers

The pollution rulers used in this analysis (700 in total= 7 stability classes times 100 speed levels) are constructed graphically by a code, *file DRAW-RULER.PAS* (figure 6).

This code gives also a wide range of useful information about the spatial characteristics of the rulers

The analysis exhibited the following very interesting characteristics of the pollution spread:

1. The **active angle**, (see figure 7) that is the minimum angle centered at the unit which covers the ruler is very small varying from 8^o to 15^o. This characteristic reduces significantly the spektrum of wind directions affecting a point/commune and highly benefits the algorithmic approach.

2. The range of the rulers varies from a few kilometers to more than 100 km depending mainly on the wind speeds. The highest values are recoreded for classes 1 and 2 when wind speed is ver low (1 m/sec or below). The corresponding affected area varies from 30 to 240 km^2 **This characteristic could exert a very negative impact to the public health and the economy if it is not appropriately encountered during assessment studies. Actually, it demands that the range of the assessment should be well above 20 km where still a load of 0.8 mg/m^3 or higher is recorded at low wind speeds and stability classes**

3. The pollutants concentration varies significantly from 0 up to 1.4 mg/m^3 The highest values are recorded for classes 1 and 2 at very low wind speed and for class 6 at medium wind speeds. For classes 1 and 2 the maximum values (above 1.1 mg/m^3) occur at a zone 10-15 km wide and at a distance 10-20 km from the unit and cover up to 30 km (table 3.1)

3.5 The solution methodology

The calculation of the values of function C and APC, at a given communal grid point P, or of function TPL on a set of grid points covering a commune or a higher level administrative region, is performed inside the spektrum of descritized pollution values which demands for the following re-expression of functions C, APC and TPL:

$$APC^*(U,P) = \sum_{s,u} F(s,u) \quad \sum_i F(di)\, C^*isu(U,P) \tag{3.3}$$

$$TPL^*(U, \mathbf{R}) = \sum_{P \in R} W(P)\, APC^*(U,P) \tag{3.4}$$

and

$$Cisu^*(U,P) = \max_{j=1,2,3,4} \ Cisu(U,Vij(P)):$$

where Vij(P) j=1,2,3,4 are the 4 vertices of the grid trapezium P belongs to (Result 3.4, see also figure 9 for an example).

The following **fathoming rules** (Results 3.5 3.6 and 3.7) increase drastically the efficiency of the solution method (speed up calculations).

Assuming from thereon that wind directions di $i=2^0,3^0,..360^0$ have been placed in increasing order of magnitude we can replace di with i^0. We evaluate next the cumulative frequency of wind i:

$$CF(i) = F(i)-F(i-1) \quad i=2^0,3^0,..360^0 \ (CF(1) = F(1)) \tag{3.5}$$

RESULT 3.5. For a given ruler (s,u) and a given point P lying at a distance s from the polluting unit U:

$$APC^{*}(U,P) = \sum_{s,u} L_{su}\ ,\ L_{su} = \sum_{j=1}^{psu} 2[CF(down(K_{j+1})) - CF[down(K_j)-1](psu-j) \quad (3.6)$$

$$TPL^{*}(U,R) = \sum_{P\in R} W(P)\, APC^{*}(U,P^{*}) \quad (3.7)$$

where $psu = C\, su^{*}(U,P')$ $P'=(s,0)$ and K_j $j= 0,1,2,.\, psu$ are the intersections of the periphery of the circle (U, s) (U center, s radius) with the iso-polluting curves of the pollution ruler (s, u) in increasing polar deviation from x axis (j=0 refers to the iso-polluting curve which lies on the x-axis); down(K) is the downward rounding of the angle (KU x-axis) to the nearest degree whereas up(K) is the upward rounding of this angle to the nearest degree

Proof. The summation over all wind direction ($i^{\circ}= 1^{\circ},2^{\circ},\ldots 360^{\circ}$) will change the relative position of P with respect to the system of coordinates in which x axis will follow each time the new wind direction i is considered. In each new position its distance from the unit U will remain constant. Hence, the point P will follow a circular trajectory that will cut the iso-polluting linear segments at the points K0, K1,...Kp. Let P_i $i=1^{\circ},2^{\circ},\ldots 360^{\circ}$ be the relative position of the grid point with respect to wind direction i. Assume that $P_i \in \overset{\frown}{K_j K_{j+1}}$ ($P_i \neq K_j$). Then $C_i^{*}(U,P) = p-j$ due to the fact that point P_i takes the value of the pollution of the nearest to x-axis iso-polluting curve; p-j is then multiplied by the corresponding frequency F(i) to get the corresponding factor in function APC^{*}. Hence if g consecutive positions P_i, say from $i1^{\circ}$ to $i2^{\circ}$ among the 360 different ones, happen to lie between the curves K_j and K_{j+1} then p-j should be multiplied by $F(i1^{\circ})+F(i1+1^{\circ})+\ldots+F(i2^{\circ})=CF(i2^{\circ})-CF(i1-1^{\circ})$ which completes the proof of the result.

What the fathoming rule introduced by Result 3.5 does is: (a) to shrink the range of summation over i to the active angle of a ruler (b) to descritize corresponding calculations to the level of grid trapezia . The fathoming power is strong enough to reduce the computational effort by as much as 20-30 times.

STABILITY	SPEED m/sec	x-RANGE km	y-RANGE km	max CONCENTR.- mg/m	at DISTANCE -x km	GRID POINTS	AREA km
1	0.1	100.2	3.3	1.4	8.9	226	232
1	0.5	81.6	1.2	0.9	5.35	101	
1	1	54.3	1.1	0.7	4.1	65	36
1	1.5	42.7	0.9	0.6	3.7	50	
1	2	35.9	0.8	0.5	3	37	
1	5	22.1	0.6	0.5	1.8	37	
1	10	15.4	0.4	0.5	1.2	37	3.8
2	0.1	100	3.6	1.3	7.6	197	
2	0.5	65.6	1.7	0.8	4.3	82	
2	1	43.1	1.2	0.6	3.2	50	
2	1.5	33.6	1	0.5	2.7	37	
2	2	28.2	0.8	0.5	3.1	37	
2	5	17.3	0.6	0.5	1.3	37	
2	10	11.8	0.4	0.5	0.9	37	
3	1	25.2	1	0.2	3.3	10	
3	2	18.6	0.8	0.4	2	26	
3	3	15.2	0.7	0.5	1.4	37	
3	4	13	0.6	0.5	1	50	
3	5	11.5	0.6	0.6	1	50	
3	10	7.7	0.4	0.6	0.8	50	
5	2	8.5	0.8	0.3	1.3	17	
5	4	5.8	0.7	0.4	0.3	35	
5	7	4.2	0.5	0.6	0.2	45	
5	10	3.3	0.4	0.5	0.2	43	
6	2	6.7	0.8	0.4	0.9	33	
6	6	3.5	0.5	1.1	0.2	83	
6	7	3.1	0.5	1.1	0.2	85	
7	2	18.7	0.8	0.4	1.7	26	
7	5	11.1	0.6	0.5	0.7	37	
7	7	9	0.5	0.5	0.5	37	
7	9	7.6	0.5	0.5	0.5	37	2

TABLE 3.1 Pollution ruler characteristics

RESULT 3.6. Consider a ruler (s,u) a wind direction di and a point P. Let a(s,u) be the active angle of the ruler (see figure 12) and θ = angle(PUdi) If $0.5a < \theta$ then C*isu(U,P)=0

Proof. P lies outside pollution ruler and hence the level of pollutants concentration in it is zero.

RESULT 3.7. Consider a commune (region) **C**= (Vi i=1,2,...k its vertices) a ruler (s,u) and a unit at location U. Let dc =min dist(Vi, U) and dr the maximum length of the ruler along the x-axis. If dc > dr then L su = 0 $\forall$ (see figure 12)

Proof. Due to the inequality and the fact that the pollution ruler has a bell-like shape (along any perpendicular direction there is only one global maximum lying on the intersection of this direction with the x-axis) all grid points of the commune lie outside ruler R(s,u) and hence their pollutants concentration level is zero.

4. APPLICATIONS IN BELGIUM - CONCLUSIONS

The models and the solution methodology introduced in the previous chapter were applied for a long range impact assessment that covered all communes of Belgium.

A pilot unit with emitted thermal flow 5 (MW), emitted pollution mass 1 kg per hour and stack height 69 m was placed in the middle of DROGENBUS commune.

For each commune of Belgium and for the country as a whole two types of measurements were taken:

(1) Maximum pollutants concentration levels in mg/m (function C)
(2) Average (per inhabitant) pollutants concentration (function APC)

The meteorological data used were random, following a homogeneous distribution. Note that random data of this type smooth out extreme values for both measurement functions. Equivalently, if the result of this impact study exhibits significant inter-communal deviations or extreme values for the above measurements its most probable that this will be due primarily to population distribution. Furthermore, real meteorological data will magnify even more such deviations or extreme values.

We have considered two different impact types on the public health:

(a) A linear type of relation between the levels of pollution loads (concentration or APC) and the impact they exert on public health. [ASSESSMENT STUDY 1]
(b) A non-linear (exponentially increasing) relation between the levels of pollution load and the impact on public health [ASSESSMENT STUDY 2].

In the second assessment study we considered also the same type of impact exerted on the economy from the burden exerted to public health from the above considered pollution loads

In this case the non-linear relationship is employed as a thumb rule so as to capture possible dis-economies of scale on the cost burden exerted to the economy from the negative impact of extreme loads of pollution on the public health.

Notice at this point that the findings of the Natural Resources Defence Council ("Breath Taking"Report, see Appendix I) suggested that the impact of atmospheric pollutants concentrations on the public health is linear for the framework of the survey (time span and spatial range).

The time span and the spatial range of the survey is rather narrow and cannot cover adequately and with absolute certainty all types, ranges and levels of impact on the health, even less to economy.

In order to throw light in the extreme possibility of being the impact non-linear, and in this case it is natural to consider dis-economies of scale of exponential rate of increment for burden receiving systems with a threshold capacity, we have decided to conclude the second assessment study in which beyond the two measurements, max and average concentration values, we have also calculated an impact to the economy measurement by multiplying average measurements by the non-linear impact function. As it is obvious, in the second assessment measurements can only be interpreted in a relative way.

ASSESSMENT STUDY 1

Pollutants concentration varied from 0 to 1.4 mg/.m^3

The maximum level of 1.4 mg was recorded in 34 out of 586 communes (6%). The level 1.3 in 11 communes (2%) whereas in 77 communes (13%) a level of 1.0 mg or higher was recorded.

ACV varied from 0 to 0.0037 mg/m^3 The communes with the highest APC levels (levels are multiplied by 10,000) are:

LINKEBEEK = 36.6	* BRUXELLES = 13.5	* BERCHEM = 8.2
FORESTVORST = 26.1	* ETTERBEEK = 12.3	* SHAERBEEK = 8.5
* DROGENBOS=25.1	SAINT-JOSSE = 12.1	ANTERLECHT = 7.2
* SINT-GILLE=23.2	.* WOLUWE = 8.9	* EVERE = 6.2

Note that in all communes with an asterisk a very high pollutants concentration value has been recorded (1.3 or 1.4 mg/m^3).

The basic conclusion from the above results is that the spatial dissemination range and deviation as well as the level of pollution loads is rather significant and unexpected, especially in the light of the random meteorological data employed.

ASSESSMENT STUDY 2

In this study by pollutants concentration we mean the transformed through the impact function measurement (called TM) and not the original physical measurement.

TM varied from 0 to 7. The maximum level was recorded in 40 communes whereas levels greater or equal to 1.4 were recoreded in 78 communes.

Transformed measurement of APC varied from 0 to 5. The communities with the highest transformed APC (values multiplied by 10,000) are:

LINKEBEEK = 6.0	SAINT-JOSSE = 3.2	UCCLE = 3.0
DROGENBOS = 5.8	SINT-GENESIUS = 3.3	WOLUWE-PIETERS = 3.0
SAINT-GILL = 4.3	BRUXELLES = 3.0	
ETTERBEEK = 3.4	BERCHEM = 3.0	

Finally the communes where the highest levels of economic impact were recorded are (the impact is given as % of the national):

BRUXELLES = 12.35%	MOLENBEEK = 3.54%
WOLUWE-PIETERS = 4.39%	EVEREE = 3.34%
JETTE = 4.31%	WATERLOO = 2.88%
ETTERBEEK = 3.64%	GANGSHOREN = 2.41%

As in the previous assessment the spatial range of impact was significant.

Comparing the two assessments, we can conclude that the non-linear impact functions reduce significantly, by smothing downwards, APC values for the majority of the communes. Note at this point that exponential type of impact functions have drastic effects on meteorological conditions that exhibit significant variance.

AS far as the theoretical and algorithmic part of the study is concerned, the computational time required for each one of the above two assessments was around **4 hours**. Note that with the conventional approach around 60000 grid points for each ruler should be scanned on average over 700 pollution rulers and for 20 different wind directions. That amounts to 840 million calculations of the IFDM function or **420** hours of computational time. The power of the applied discretization structure and the fathoming rules have significanty reduced the computational time of the impact assessment.

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