The RAINS model,
uncertainty and optimisation

Report

Ministère de l'écologie et du développement durable

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EXECUTIVE SUMMARY

The RAINS (Regional Air Pollution INformation and Simulation) model has been developed by IIASA (International Institute for Applied Systems Analysis, Laxenburg, Austria) as a tool for the integrated assessment of alternative strategies to reduce atmospheric pollution in Europe. The current version of this model describes the pathways of emissions of sulphur dioxide, volatile organic compounds (VOC), nitrogen oxides, ammonia and particulate matter and explores health and ecosystems' impacts of particulate pollution, acidification, eutrophication and tropospheric ozone[1].

This model includes three modules: the emission-cost module; the acid deposition, eutrophication and ground-level ozone impact (on human health and ecosystems) module; and the optimisation module. The latter defines national emission ceilings that enable, theoretically, to reach some user-defined environmental targets at a minimal cost.

This model has a strong political importance: it has been used several times since the beginning of the 1990s as a basis for the definition of European emission reduction strategies. Two of the most recent political applications are the definition of the national emission ceilings (for sulphur dioxide, nitrogen oxides, ammonia and non methanic volatile organic compounds) set by the Gothenburg Protocol in 1999 and those set by the European Directive on National Emission Ceilings for certain atmospheric pollutants in 2001.

The great work undertaken during the last few years to develop the RAINS model has enabled it to give very helpful information about more and more complex issues. Nevertheless it suffers from several drawbacks and limitations. The optimisation module is now exploited only to define national emission ceilings derived from environmental constraints set for each grid cell. Yet, establishing other kinds of emission reduction strategy and running the optimisation module with simpler environmental constraints than those used now is possible. This could help the model deliver more transparent and, in many cases, more robust, results.

This report suggests different possible ways forward:

- Increase the transparency about the RAINS model and its utilisation.
- Introduce only the emission reduction costs in the goal function of the optimisation module. This implies suppressing the term aimed at minimising the environmental target violation.
- Use simple and transparent optimisation scenarios. Run the optimisation module with various optimisation scenarios of this kind to give several views of the same issue.

This report is more or less an updated translation of a previous work: Soleille, S., Brignon, J.-M., Farret, R., Landrieu, G., Le Gall, A.-C., Rouïl, L. 2003. L'IIASA et la modélisation intégrée de la pollution atmosphérique transfrontière - Bilan et évaluation. INERIS, report no DRC/MECO - 2003 – 45981/note_IIASA.

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[1] The RAINS model is in constant evolution so describing the most up-to-date of its versions was not always possible. Here, the version referred to is mainly that used in 1999 and 2000 to prepare the Gothenburg Protocol and the National Emission Ceilings directive. It did not include particulate matter. Nonetheless, we have tried to take into account more recent modifications of the model as far as possible.

GLOSSARY

AOT40:	Accumulated concentration of ozone over a threshold of 40 ppb (indicator for vegetation-related excess ozone exposure)
AOT60:	Accumulated concentration of ozone over a threshold of 60 ppb (indicator for health-related excess ozone exposure)
CAFE:	Clean Air For Europe
CCE:	Coordination Center for Effects
CIAM:	Centre for Integrated Assessment Modelling
CITEPA:	Centre interprofessionnel technique d’études de la pollution atmosphérique
CLRTAP:	Convention on Long-Range Transboundary Air Pollution
EGTEI:	Expert Group on Techno-Economic Issues
EMEP:	Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air pollutants in Europe
GDP:	Gross Domestic Product
IFARE:	French-German Institute for Environmental Research
IIASA:	International Institute for Applied Systems Analysis
MFR:	Maximum Feasible Reduction
NEC:	National emission ceilings
PM:	Particulate Matter
RAINS:	Regional Air Pollution INformation and Simulation
RIVM :	National Institute for Public Health and the Environment (Netherlands)
TAP:	Transboundary Air Pollution
TFIAM:	Task force on integrated assessment modelling
UN ECE:	United Nations Economic Commission for Europe
VOC:	Volatile organic compounds
WGE:	Working group on effects
WHO:	World Health Organisation

INTRODUCTION

The RAINS (Regional Air Pollution INformation and Simulation) model is a tool for the integrated assessment of alternative strategies to reduce atmospheric pollution in Europe. The current version of this model describes the pathways of emissions of sulphur dioxide (SO_2), volatile organic compounds (VOC), nitrogen oxides (NOx), ammonia (NH_3) and particulate matter (PM) and explores health and ecosystems' impacts of particulate pollution, acidification, eutrophication and tropospheric ozone. It can be used in two modes: in the "scenario analysis" mode, it calculates the impact of atmospheric pollution on human health and ecosystems and evaluates the costs of various emission reduction strategies; in the "optimisation" mode, it calculates which way of distributing emission reductions by country enables to reach some user-specified environmental targets with the minimum cost.

This model has a strong political importance: it has been used several times since the beginning of the 1990s as a basis for the definition of European emission reduction strategies. Two of the most recent political applications are the definition of the national emission ceilings (for sulphur dioxide, nitrogen oxides, ammonia and non methanic volatile organic compounds) set by the Gothenburg Protocol[2] in 1999 and those set by the Directive on National Emission Ceilings for certain atmospheric pollutants[3] in 2001.

This report aims at giving a brief overview of the RAINS model, the way it is used and some of its limitations. In the first part of this report, a brief overview of the model RAINS is given. In the second part, the importance of the uncertainties of the model is outlined. Then a focus is made on the optimisation module in the third part and, in the fourth part, on the environmental constraints used in this module.

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[2] Protocol designed to abate acidification, eutrophication and ground-level ozone.

[3] Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants.

1. AN EVOLVING MODEL IN AN EVOLVING CONTEXT

1.1 BRIEF PRESENTATION OF THE MODEL

The RAINS (Regional Air Pollution INformation and Simulation) model has been developed by IIASA (International Institute for Applied Systems Analysis, Laxenburg, Austria) as a tool for the integrated assessment of alternative strategies to reduce acid deposition in Europe (and in Asia).

The current version of this model describes the pathways of emissions of sulphur dioxide (SO_2), volatile organic compounds (VOC), nitrogen oxides (NOx), ammonia (NH_3) and particulate matter (PM) and explores health and ecosystems' impacts of particulate pollution, acidification, eutrophication and tropospheric ozone.[4]

Europe (41 countries) is divided into a regular grid of 50 km x 50 km cells (EMEP[5] grid). The time scale runs from 1990 to 2030.

This model includes three modules:

- the emission-cost module (EMCO);
- the acid deposition, eutrophication and ground-level ozone impact (on human health and ecosystems) module (DEP);
- the optimisation module (OPT).

The RAINS model can be used in two modes:

- The "scenario analysis" mode. From given activity scenarios (real or hypothetical), the model calculates the impact of atmospheric pollution on human health and ecosystems. It can also evaluate the costs of emission reduction strategies.
- The "optimisation" mode. From given environmental targets, the model calculates which way of distributing emission reductions by country enables to reach the targets with the minimum cost.

The figure thereafter summarises the global process of the model (enclosed in the dotted line) and the interaction of the three modules. Horizontally, the input data are indicated at the top and the output data at the bottom. Vertically you can see the "scenario analysis" mode on the left (i.e. the EMCO and DEP modules) and the "optimisation" mode on the right (i.e. the OPT module).

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[4] The RAINS model is in constant evolution so describing the most up-to-date of its versions was not always possible. Here, the version referred to is mainly that used in 1999 and 2000 to prepare the Gothenburg Protocol and the National Emission Ceilings directive. It did not include particulate matter. Nonetheless, we have tried to take into account more recent modifications of the model as far as possible.

[5] Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air pollutants in Europe.

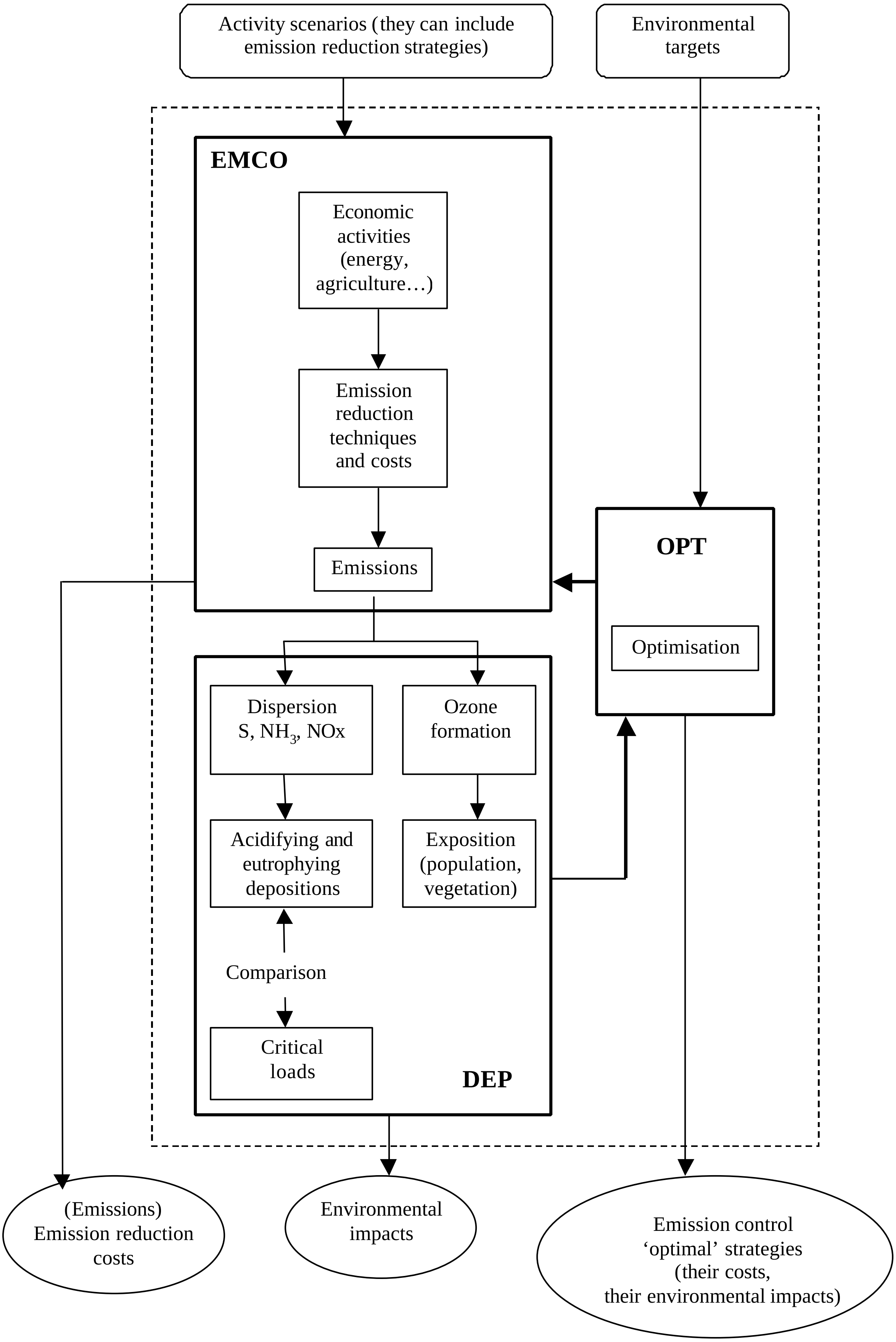

Figure 1. Schema of the RAINS model

1.2 AN EVOLVING MODEL

1.2.1 Past evolution

The RAINS model was originally developed mostly to satisfy the needs of the CLRTAP.[6] The European Commission has been using the RAINS model as well since the mid-1990s to define some atmospheric pollution reduction strategies.

The CLRTAP first protocols (Sulphur in 1985, NOx in 1988, VOCs in 1991) aimed at reducing uniformly the national emissions (compared with a base year). This approach was criticised, partly because it was not cost-effective. So it changed in 1994, for the Second Sulphur Protocol:

- the new approach was *effect-based*[7] (i.e. the targets are expressed as reduction of effects and not any longer as reduction of emissions);
- the level of emission reduction was driven by the impacts of atmospheric pollution on the *most sensitive* ecosystems;
- the new approach aimed at finding emission reduction strategies that would attain the environmental targets in a cost-minimising way.

One of the key factors driving the adoption of such an approach was the development and the political approval of the critical load concept. The critical loads quantify the ecosystem capacity to absorb the acidifying (or the eutrophying) depositions without damage. They give a threshold to maintain long-term sustainability conditions for ecosystems.

In the beginning, the model took into account only one effect, acidification, and one pollutant, sulphur dioxide. In 1996, the formation of tropospheric ozone was integrated in the model. The number of effects and of pollutants increased progressively. In 1997, in the third Interim Report, the optimisation module was able to deal with four pollutants (NOx, SO_2, NH_3, VOCs) and four effects: acidification, eutrophication[8], ozone impact on human health (expressed as AOT60) and ozone impact on ecosystems (expressed as AOT40).

1.2.2 On-going developments

Many developments are currently under process. RAINS can now take into account one more effect, the impact of particulate matter on human health, and several new pollutants: particles, CO_2, CO, CH_4, etc.

The extension of the RAINS model to greenhouse gases has provoked important changes in the model. The mathematical formulation of the optimisation problem has changed: the

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[6] Convention on Long-Range Transboundary Air Pollution (CLRTAP), signed in 1979, within the framework of the United Nations Economic Commission for Europe (UNECE).

[7] To be more accurate, we should say it is 'exposition-based', instead of 'effect-based'. As a matter of fact, the indicators used to evaluate acidification, eutrophication, health and ecosystem exposure to ozone quantify expositions and not effects. Things are different with particulate matter, since the indicator considered is the reduction of life expectancy due to exposure to PM.

[8] Nevertheless, in most cases, the optimisation process has neglected eutrophication.

decision variables are no longer the emissions (and the authorised environmental target violations) but the application rates of the emission control measures. Furthermore the model can take into account some structural measures (fuel substitution, energy efficiency improvements and so on) as emission control options, beside technical measures. Behavioural changes (e.g. changes in preferences for societal life styles, traffic restriction, pollution taxes, emission trading systems) remain outside the range of the model. They are reflected through alternative exogenous activity scenarios. Nevertheless, the extension of the RAINS model to greenhouse gases leads to a "new formulation of the RAINS model [that] allows simulation of a variety of flexible mechanisms for controlling GHG and air pollution emissions. This includes, *inter alia*, the possibility of simulating carbon taxes for all greenhouse gases, emission taxes for conventional air pollutants, trading of carbon and other greenhouse gases within selected countries in Europe (e.g., the EU), and the clean development mechanism of the Kyoto protocol where emission permits could be acquired from Non-Annex 1 countries" (Klaassen et al., 2004).

Furthermore, within a few years, RAINS should be able to use critical loads in a dynamic framework, to integrate climate change, to study the effects of ozone and particles at the urban scale, etc.

These numerous changes are partly exposed in the latest two reports published by IIASA (Amann et al., 2004; Klaassen et al., 2004) but their integration in the RAINS model does not seem completely achieved as of now. IIASA has not released any complete optimisation results including these new developments yet. Therefore this report is mainly focussed on the RAINS model as it was during the negotiations for the Gothenburg Protocol and the NEC directive even though it tries to take into consideration as much as possible these on-going developments.

1.3 ACHIEVEMENTS OF THE RAINS MODEL

1.3.1 A very useful tool for decision-makers

The RAINS model is a complex and powerful tool and its utilisation, both in the "scenario analysis" mode and in the "optimisation" mode has proved to be very helpful in studying and defining Europe-wide emission reduction strategies.

In the scenario analysis mode it can describe the environmental effects and the costs of different emission reduction strategies. Now, it can also estimate the cross-effects between climatic change policies and atmospheric pollution ones.

The optimisation mode makes the RAINS model an even more useful decision-making tool (of course, within its validity range), for at least two main reasons:

- it enables the model to determine emission reduction strategies stemming from user-supplied environmental and health targets ('effect based', or, more accurately, 'exposition based');
- it enables to try to determine which are the cost-minimal emission reduction strategies, the environmental and health targets being given.

1.3.2 Political applications

The political applications of the RAINS model took place both in the framework of the

Geneva Convention (Second Sulphur Protocol in 1994, Gothenburg Protocol in 1999) and in that of the European Union (Ozone Strategy, National Emission Ceilings directive in 2001[9]).

The RAINS model will be used to define the thematic strategy in the CAFE (Clean Air For Europe) programme (mid-2005), to review the NEC directive (2006) and to review the Gothenburg Protocol.

2. UNCERTAINTY

2.1 EXISTING STUDIES ON UNCERTAINTY

IIASA published in 2001 a study about the uncertainties in the RAINS model, in scenario analysis mode, as far as acidification is concerned (Suutari et al., 2001). IIASA propagated the uncertainties of the input data and that of the model to the acidifying deposition estimates.[10]

We compare only a part of the results of this study, that is the estimation of the uncertainties for the emission inventories in 2010, with those of a French study (CITEPA, 2002), a Finnish one (Syri et al., 2000) and a Norwegian one (Rypdal, 2002).

First we can note some methodological differences:

- the uncertainties on emission factors used by IIASA are much lower than those recommended by the UNECE/CORINAIR methodological guidebook (Pulles et al., 2001);
- the methodology to propagate uncertainties used by IIASA seems different from that recommended by the UNECE/CORINAIR methodological guidebook and used for instance by CITEPA.

In the following table, we compare the uncertainty estimates for French emissions by IIASA and those calculated by CITEPA (Oudart et al., 2002), using the CORINAIR methodology.

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[9] Directive 2001/81/CE of 23rd October, 2001.

[10] The methodology used here by IIASA is only valid for linear models. Therefore it can be applied to the acidifying deposition calculations but not to the ozone formation calculations.

Table 1. Uncertainties in the French emission inventories calculated by IIASA (for the years 1990 and 2010) and by CITEPA (for the year 2010 only)

	IIASA		CITEPA
	1990	2010	2010
SO_2	6%	16%	10%
NOx	11%	12%	46%
VOC[11]	–	–	30%
NH_3	11%	14%	80%

Syri et al. (2000) studied the uncertainties of the RAINS model, in scenario analysis mode for acidification in Finland. They find higher results than IIASA.

Table 2. Uncertainties in the Finnish emission inventories calculated by IIASA (for the years 1990 and 2010) and by Syri et al. (for the year 2010 only)

	IIASA		Syri et al.
	1990	2010	2010
SO_2	8%	17%	5%
NOx	9%	11%	15%
NH_3	10%	13%	40%

Rypdal (2002) also estimated the uncertainties for emission inventories in Norway for NOx, SO_2, VOCs and NH_3.

Table 3. Uncertainties in the Norwegian emission inventories calculated by IIASA (for the years 1990 and 2010) and by Rypdal (for the years 1990, 1998 and 2010)

	IIASA		Rypdal		
	1990	2010	1990	1998	2010
SO_2	17%	30%	4%	4.2%	5%
NOx	11%	16%	12%	12%	12%
COV	–	–	18%	21%	15%
NH_3	14%	18%	21%	18%	21%

The methodological discrepancies aforementioned may explain the contrasts between IIASA's estimates on the one hand and those by Syri et al., Rypdal and CITEPA on the other:

- according to IIASA, in 2010, the uncertainties on SO_2 emissions are the most important

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[11] In this report, IIASA do not estimate the uncertainties for the VOCs emissions.

ones whereas according to CITEPA, Rypdal and Syri et al., the estimations concerning SO_2 are the less uncertain;

- the estimates by CITEPA and Syri et al. are much higher that those by IIASA (as much as five times higher as far as NH_3 is concerned according to CITEPA).

We can note as well that according to IIASA, as far as NOx and NH_3 are concerned, uncertainties are only a bit higher for the year 2010 (projection) than for the year 1990 (inventory for a past year).

IASA drew the following conclusions, for all the uncertainties calculated in this report (i.e. those for emissions, for depositions and for ecosystem protection):

- Uncertainty estimation is very difficult. As a matter of fact, it is more uncertain than the model output for which it is realised.
- Errors compensate each other to quite a great extent. The more data of similar importance are aggregated, the greater the compensation potential is. Because of this, in several countries, SO_2 emission inventories are more uncertain than those of NOx, or even than those of NH_3. That is because SO_2 emissions are dominated by one or two principal sources whereas NOx emissions are emitted by a large number of sectors of similar importance. In the same way, sectorial emissions are more uncertain than national emissions.

2.2 UNCERTAINTY MARGINS AND VARIATIONS IN THE SUCCESSIVE IIASA INTERIM REPORTS

2.2.1 Uncertainties and changes in the input data

In this section we compare national emissions given by IIASA in two different reports: the first Interim Report to the European Commission (October 1996) and the 8th Interim Report to the European Commission (February 2000).

The national emissions considered for the year 1990 are different in the two reports. As far as NH_3 is concerned, for 6 out of the 15 countries of the European Union, the difference between the emissions in the two reports is greater than the uncertainty margin estimated by IIASA in the aforementioned report (Suutari et al., 2001). For France, for instance, IIASA assumes that the uncertainty margin on NH_3 emissions in 1990 is equal to 11%. Between 1996 and 2000 the value used by IIASA for French NH_3 emissions in 1990 changed by 25%. As far as NOx are concerned, the difference between the emissions in the two reports is greater than the uncertainty margin estimated by IIASA for 6 countries out of 15.

We can see on the following graph the variations (in %) between the NH_3 emission inventories for the year 1990 given by IIASA in the two aforementioned interim reports and the uncertainty margin for the NH_3 emissions in 1990 estimated by IIASA in its 2001 report about uncertainty.

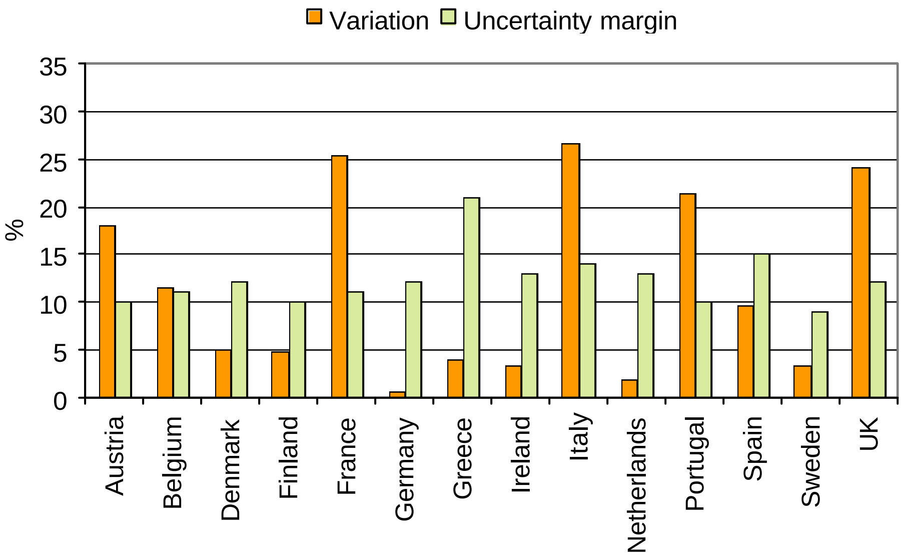

Figure 2. Variations (in %) between the NH_3 emission inventories for the year 1990 given by IIASA in its 1st Interim report (1996) and those given in its 8th Interim Report (2000) and uncertainty margins for the NH_3 emission in 1990 calculated by IIASA in its 2001 report

For the projected emissions in 2010 (the REF situation), the changes between the two reports are even more important. As far as SO_2 is concerned, emission variations between the two reports are higher than the uncertainty margins calculated by IIASA for 10 countries out of 15 (see the following graph). As far as NOx are concerned, they are higher for six countries and as far as NH_3 is concerned, they are higher for seven countries.

The SO_2 emissions in 2010 (REF situation) for the six biggest emitters of the European Union can be seen on the following graph. For each country, the two orange bars represent the SO_2 emissions in 2010 in the REF situation. The first one represents the emissions IIASA gave in the first Interim Report (IIASA, 1996). On this bar, the black line represents the uncertainty margin, estimated by IIASA in its 2001 report. The second bar represents the emissions IIASA gave in the eighth Interim Report (IIASA, 2000). It can be seen that for these six countries, the difference between the emissions calculated in the first Interim Report and those calculated in the eighth one is greater than the uncertainty margin.

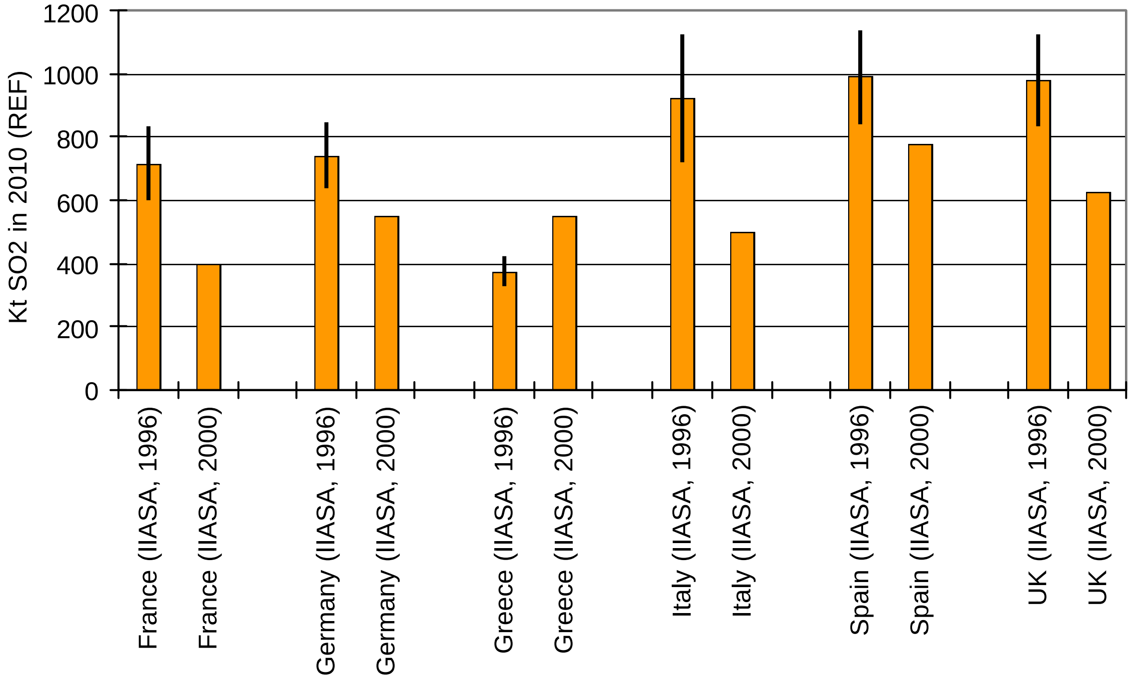

Figure 3. SO_2 emissions in 2010 in the REF situation and uncertainty margins

2.2.2 Sensitivity of the optimisation results to the uncertainty of the input data

No evaluation of the uncertainties associated with the optimisation mode seems to have been conducted.

We tried to estimate the sensitivity of the optimisation results to the input data. We compared the optimisation results in the 6th, 7th and 8th Interim Reports (published respectively in 1998, 1999 and 2000). We consider the scenarios F1, H1 and K1. They are identical, except for the input data that was actualised. The national emission ceilings calculated in these three reports, to reach the same environmental targets, vary from one report to another, for a single country, on average by 14% for NOx, by 10% for SO_2, by 7% for VOCs and by 3% for NH_3. French emission ceilings are modified by 17% for SO_2 emissions, by 12% for NOx emissions, by 1% for NH_3 emissions and by 8% for VOCs emissions. For some countries, the variations are much greater: we can observe a 60% change for the SO_2 Danish emission ceiling (i.e. 29 kt) and even a 128% change for the Portuguese NOx ceiling (i.e. 143 kt)…

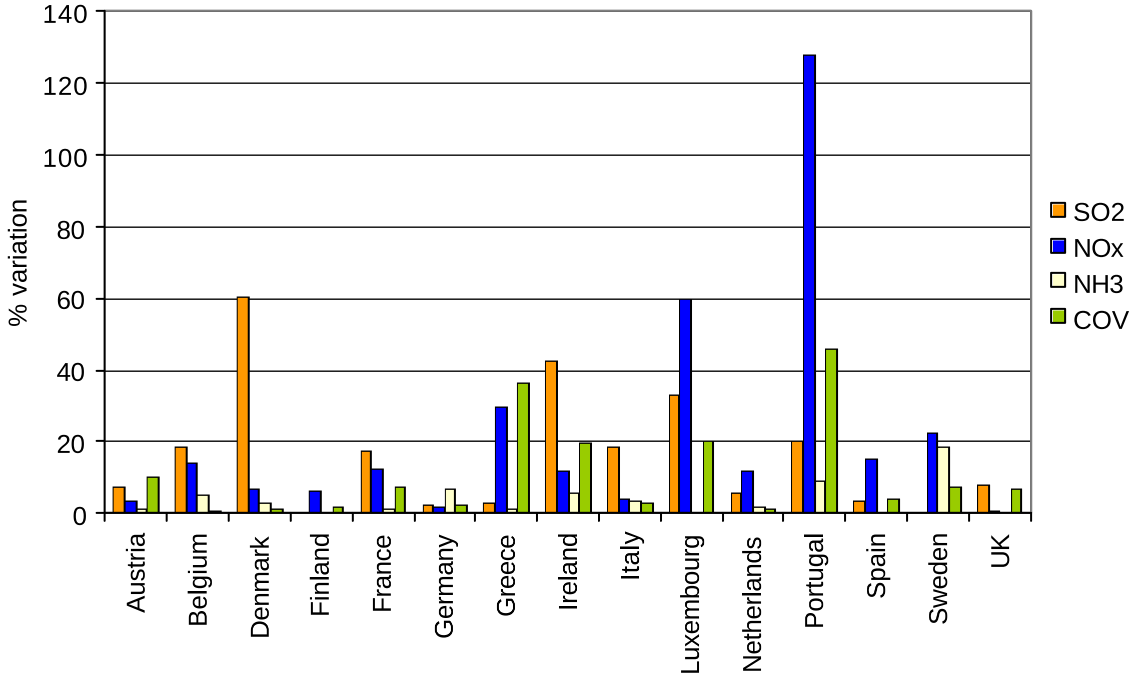

Figure 4. Variation (in %) of the optimised national emission ceilings (for the year 2010) calculated by IIASA between 1998 and 2000

It has been shown before that the fact that the constraints are defined for a great number of grid cells increases this sensitivity (Landrieu, 1998).

2.3 CONCLUSION ON UNCERTAINTIES

IIASA released a report to estimate the uncertainties of the RAINS model in scenario analysis mode for acidification only. These uncertainties are very difficult to evaluate. Those concerning ozone formation are even more difficult to estimate since the issue to be modelled is more complex. The uncertainties of the optimisation mode are not mentioned.

Other research teams published uncertainty calculations for some of the emissions data studied by IIASA. These studies usually give uncertainty margins higher than those estimated by IIASA. Furthermore, in numerous cases, changes in national emission inventories calculated by IIASA in its successive Interim Reports are higher than the uncertainty margins estimated by IIASA for these emissions.

In a nutshell, it seems that the uncertainties calculated by IIASA are quite underestimated or that they neglect some biases in the emission calculations. Besides the model now integrates the particulate matter as well and the uncertainty on PM emission inventories may be much greater than those for NOx or SO_2 emission inventories.

3. THE OPTIMISATION MODULE

3.1 THE PRESENT STATE OF THE RAINS OPTIMISATION MODULE

3.1.1 Aim

The optimisation module gives the cost-minimal repartition of the emissions reductions in Europe, by country, in such a way that in each cell of the EMEP grid, acidification, eutrophication and exposure to ground-level ozone should be kept below specified environmental targets. These targets can be specified for one pollutant or for a set of pollutants (multi-pollutants/multi-effects optimisation).

To achieve this objective, the optimisation module minimises a goal function, acting on certain decision variables, from certain input data, and complying with different constraints. In other terms, the optimisation module finds out for which value(s) of the decision variables, the goal function is minimal and the constraints are respected.

We are going to describe successively the input data, the decision variables, the output data, the constraints and the goal function used in the RAINS optimisation module.

3.1.2 Variables

3.1.2.1 Input variables

Among the input data, a line can be drawn between physico-chemical and economical data on the one hand and environmental targets on the other.

3.1.2.1.1 Physico-chemical and techno-economical input data

The physico-chemical and economical data are:

- activity scenarios for given target years (2010 during the latest negotiations), that is prospective data about energy consumption[12], industrial activity, agriculture sector in future years;
- national cost curves[13] for a given set of energy and agriculture scenarios;
- data describing in a simplified way the transfer of pollutants between their emission and their deposition (or their formation in the case of ozone). The transfer coefficients, expressed in a matrix-form are derived from the EMEP model.

Until now, the cost curves were calculated by IIASA from techno-economical data compiled by IIASA as well. Now the network of experts EGTEI[14] is in charge of collecting

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[12] The energy scenarios are calculated by the PRIMES model.

[13] Each cost function defines its domain by specifying lower and upper bounds for its argument(s). This implicitly defines lower and upper bounds for all emissions that are used as bounds defined in paragraph ‘Constraints’.

[14] This network of experts (Expert Group on Techno-Economic Issues), led jointly by CITEPA (Centre interprofessionnel technique d’études de la pollution atmosphérique) and IFARE (Institut franco-allemand de recherche sur l’environnement), was officially launched on 30th April 2002.

the techno-economical data and IIASA is still in charge of calculating the cost curves from these data. In 2001 EGTEI started to collect information on emission control options in a systematic way, to review the information with national and industrial stakeholders and to prepare national data for direct input into RAINS. However, due to the considerable complexity, the amount of data demanded by the approach and the difficulty in integrating this new data into RAINS, up to now, RAINS has introduced information from EGTEI only on a limited number of activity sectors: mobile road transport, off-road sources, the glass industry and solvent use (Amann et al., 2004).

3.1.2.1.2 Environmental input data

The other set of input data is the environmental targets. These targets concern exposure to ground-level ozone, acidification and eutrophication[15]. The optimisation module will contrive to reach the targets at a minimum cost. In a study on the economic evaluation of the NEC Directive (Amann et al., 1999a), IIASA gave the results of the optimisation using different sets of environmental targets (that are called scenarios[16]):

- a central scenario (H1) that sets the same relative improvements in all the grid cells compared to a baseline year (‘gap closure concept’) [17];
- the scenarios H2 and H3, quite similar to the scenario H1 but with slight variations in the targets;
- scenarios in which one single effect is privileged.

The corresponding solutions are greatly driven by the concept of ‘gap closure’ and by the level of the environmental targets.

3.1.2.2 Decision variables

The decision variables are the variables that the optimisation module lets vary during the optimisation phase: the module finds out for which value(s) of those variables the overall costs of emissions reduction strategies are minimal.

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[15] During the study to prepare the National emission ceilings (NEC) directive, there were only constraints for acidification and ozone exposure and not for eutrophication (Amann et al., 1999a).

[16] The word ‘scenario’ can mean three different things in IIASA reports:

- *activity scenarios* for a future year (e.g. 2010), i.e. previsions of the economic activity in 2010;
- *emissions reduction strategies* in 2010, i.e. some previsions of the emissions of the different countries in 2010;
- *sets of optimisation constraints* that are used as input data for the optimisation module; these sets enable this module to find some emissions reduction strategies that can be compared with other emissions previsions.

[17] This scenario H1 includes different objectives:
– Reduce in 2010 the area of ecosystems non-protected against acidification by at least 50% compared to 1990.
– Reduce the AOT60 (Accumulated concentration of ozone over a threshold of 60 ppb, the indicator for health-related excess ozone exposure) by two thirds between 1990 and 2010.
– Reduce the excess AOT40 (Accumulated concentration of ozone over a threshold of 40 ppb, the indicator for vegetation-related excess ozone) by one third between 1990 and 2010.
This scenario does not include any target for eutrophication.

Until recently the decisions variables belonged to two types:

- emissions of different pollutants;
- limited violations of environmental targets.[18]

Now, following the extension of the RAINS model to greenhouse gases, the decision variables are the implementation rates of emission control measures (technical and structural measures).

3.1.2.3 Output

The optimisation module gives three kinds of output:

- the optimal emissions reduction strategy (usually expressed as a set of national emission ceilings for each country and each pollutant);
- the total cost and the marginal costs for each country;
- the exposures (exposure to ground-level ozone, acidifying and eutrophying compounds) in each receptor cell of the EMEP grid after the optimisation.

3.1.3 Goal and constraints

3.1.3.1 Constraints

There are three kinds of constraints:

1) Emissions have to remain between a lower bound and an upper bound (these bounds are specified in the cost curves, they are implicitly defined by the definition of the domain of the cost functions).
2) Violations of targets are constrained at each cell by corresponding lower and upper limits specified for each target type and for each cell.
3) Exposures (acidification, eutrophication[19] and exposure to ozone) have to be lower than the sum of the environmental targets plus the maximum allowed violations of the targets.

3.1.3.2 Goal function

The goal function is the mathematical function that is minimised during the optimisation process. Initially, it included only one term, which corresponded to the total cost of the emission reduction strategies. Thus only the costs were minimised.

As successive modifications were brought to the module, other terms were added to this goal function. When it was decided to allow some violations of the environmental targets,

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[18] These violations have been introduced in the optimisation module to grant it some flexibility: the strict compliance of environmental targets may produce more costly solutions caused by some constraints active only very locally in one or two receptor cells of the EMEP grid. Nevertheless the sum of the constraints at a country level is not allowed to be modified: if one constraint is relaxed, an equivalent surplus of targets in another receptor cell in the same country has to balance it (compensation mechanism).

[19] For the preparation of the NEC directive there were constraints only for acidification and ozone exposure and not for eutrophication.

a term was added in the goal function to minimise, beside the costs, these target violations. A third term in this goal function was introduced as a mathematical artefact to select the most stable solutions.

The module aims at reaching three goals at the same time:

1) minimisation of the total costs of the emission reduction strategies;
2) minimisation of the violations of environmental targets;
3) stabilisation of the solutions.

Each of the three terms of the goal function is multiplied by a coefficient, to set the relative weight of these three objectives. Thus, if for instance the target violation minimisation term is given a high weighting coefficient and the cost minimisation term a lower one, the module emphasises the compliance of the environmental targets compared to the minimisation of costs (and vice versa).

According to one of IIASA's latest reports, the optimisation mathematical formulation has recently changed to be able to integrate greenhouse gases (Klaassen et al., 2004). Now the goal function includes perhaps only one term, that of cost-minimisation.

3.2 SOME SHORTCOMINGS OF THE OPTIMISATION MODULE

3.2.1 What has to be included in the goal function?

The RAINS model includes in the goal function, beside cost minimisation, the minimisation of target violations[20]. These two terms are weighted by given coefficients. These weighting coefficients have probably a strong influence on the optimal solutions obtained.[21] An alternative and more transparent methodology could be to include only the cost minimisation in the goal function. In that case, the minimisation of target violations should belong to the constraints. This technique would avoid the need of the weighting coefficients.

3.2.2 Adjustment variables

RAINS includes adjustment variables (weighting of the three terms in the goal function, stabilisation term, etc.) so as to give 'cleaner' solutions, i.e. solutions that have the following properties:

- they are not constrained by the environmental constraints in too little a number of grids;
- two different solutions remain close from each other when the input data they are derived from is close (stability of the solutions).

The choice of these variables can modify greatly the obtained solution. It is therefore of the utmost importance that the way these coefficients are chosen should be explained as clearly and as transparently as possible, both before running the model and after the

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[20] And stabilisation of solutions.

[21] Furthermore by including these two terms in the goal function, we implicitly strike a balance between the cost of the policies and the constraints violation in a few grid cells.

optimisation, while giving the results.

3.2.3 Unstable solutions

There should not be a preliminary elimination of some unstable solutions through the adjustment variables, even if the aim is to give results as clear as possible. Unstable solutions, despite being unstable, are as optimal as more stable ones. It is normal and expected that a more or less linearised problem, such as that the RAINS model deals with, should give some unstable solutions.[22] The mathematical process leading to only one optimal solution, despite apparently reassuring, can hide this kind of behaviours that are perfectly normal mathematically speaking, but that can seem disturbing from the decision makers' point of view.

The unstability of some solutions should be emphasised instead of being hidden. Decision-makers have to be aware that different solutions can be optimal or quasi-optimal, while being very different from each other.[23]

3.3 SUGGESTED DEVELOPMENTS - A MORE TRANSPARENT AND LESS COMPLEX MODEL

This module was originally developed to deal with quite a 'simple' (or at least linear) problem, that of acidification. Some political targets (possibility to make some multi-pollutants multi-effects modelling) made it more and more complex, including the ozone formation (and particulate matter more recently), which is modelled with equations much more complex than acidification or eutrophication (introduction of some non-linear terms). This growing complexity led to the adjunction of mathematical artefacts to make the module more easy-to-use. It has contributed to make it less and less transparent and more and more arguable (Førsund et al., 2002).

We can give a few ideas to use the optimisation module in a more efficient and more transparent way:

- Give more scientific data about the optimisation module, especially about the algorithm that is used.
- Give more details when disclosing results. For instance, when optimisation is conducted with constraints by grid cell, the quantified impacts on human health and on the environment in each single grid cell could be given.[24]
- Change the goal function to avoid using weighting coefficients that partly set the solution a priori and that strike a balance between costs and constraint violations.

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[22] Actually a linear optimisation model tends to give 'corner solutions'; the solutions quite often 'jump' from one corner to another. In the appendix B we give a very simple example of an optimisation problem giving such unstable solutions, each of them being perfectly optimal.

[23] A sensitivity analysis cannot be treated in the same way for the scenario and the optimisation modes: with the scenario mode, such an analysis should give a continuum of solutions, whereas with the optimisation mode, such an analysis can give optimal solutions very different one from the other but the solutions in between are not necessarily optimal. The appendix B gives a very simple example of such a phenomenon.

[24] These results are now given as maps. The presentation of the results as tables, how fastidious it may be, gives more precise information. These data do not need to be available in all interim reports, but at least on the IIASA's web-site.

4. THE OPTIMISATION CONSTRAINTS

4.1 THE PRESENT OPTIMISATION CONSTRAINTS

4.1.1 The drivers of the optimisation constraints

4.1.1.1 How the sets of optimisation constraints are defined

The long-term environmental objective is that, everywhere in Europe, acidifying and eutrophying depositions should be inferior to critical loads and that ozone concentrations should be inferior to environmental and health standards. When defining strategies for the Gothenburg Protocol and the NEC directive, attaining these objectives in 2010 seemed to be impossible. So it was necessary to define interim targets.

These interim targets have been defined bit by bit. The first idea was to find strategies based on a reduction of effects, i.e. emission reduction strategies that could lead to environmental effects that should comply with some given reduction of the environmental impact on human health and ecosystems. These targets had to be defined by striking a balance between:

- giving the priority to the most polluted zones by setting uniform absolute exposition limits;
- obtaining relative improvements compared with a reference situation; these relative improvements being equal everywhere (gap closure concept).

The sets of optimisation constraints that were chosen mix these two kinds of targets. These sets of constraints have been modified to take into account a few particularities of the optimisation process. The first few optimisation runs gave solutions in which a very little number of grid cells determined the results for the whole Europe. The strict compliance with the constraints in each grid cell (even though the targets were over-achieved in most of the other grid cells) led to quite important global overcosts. So the compensation principle was introduced. The diversity of the meteorological conditions and its impact on ozone formation, the low level of the MFR[25] in a few grid cells are other factors that led to changes in the definition of the sets of optimisation constraints.

4.1.1.2 The 'gap closure' concept

The gap closure means closing, or at least reducing, the gap between the actual situation and the long-term target, by at least a given percentage, in all the cells of the EMEP grid.

As far as ozone is concerned (health and vegetation exposures to ozone), there is only one kind of gap closure, i.e. the gap closure of AOT (40 or 60), that is a reduction of the cumulated ozone exposure above a threshold.

For acidification and eutrophication, we can define three kinds of gap closure, depending on which gap we consider:

- deposition gap closure; this concept was used for the Second UN/ECE Sulphur

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[25] Maximum feasible reductions, that is the most important reductions that are technically feasible.

Protocol in 1994;[26]

- ecosystem area gap closure (gap closure of the unprotected ecosystems area); this concept was used to define the European Union Acidification Strategy;
- accumulated acidification exceedance gap closure, that is the acidifying depositions above the critical loads times the area of the ecosystems where theses depositions occur (this concept has been the most frequently used one for a few years; it was used to prepare the UN/ECE Gothenburg Protocol and the NEC directive) (Posch, 1999).

These three kinds of gap closure can be used separately or together. For the NEC directive the set of optimisation constraints defined by IIASA used at the same time the last two kinds of gap closure (gap closure of unprotected ecosystems area and gap closure of excess of accumulated deposition).

4.1.1.3 Optimisation by grid cell

One key point of the sets of optimisation constraints studied by IIASA is that environmental constraints are set **for each single grid cell**. It aims at setting targets for the most polluted zones.

In other words, priority is set on lowering pollution in the most polluted zones instead of decreasing pollution globally.

4.1.1.4 Flexibility, compensation

A strict application of the optimisation by grid cell leads to solutions that are determined by the constraints in a very little number of grid cells. Several mathematical means have been used to correct this. The most important one is the compensation mechanism: the environmental targets of individual grid cells can be exceeded provided that such exceedances are balanced by additional environmental improvements (more than meeting the targets) at other grid cells within the same country.

Some other mechanisms are used to avoid that these flexibility mechanisms should give too much flexibility: a minimum improvement percentage is set, a term to minimise the constraint violation is integrated in the goal function.

Thanks to these mathematical corrections, the model avoids giving excessive or aberrant solutions. But they have serious drawbacks: they increase the complexity of the constraints therefore making the set of optimisation constraints less transparent; they introduce mathematical artefacts that modify the solutions (that is what they are for) to an extent that is difficult to evaluate.

4.1.2 Different sets of optimisation constraints

4.1.2.1 Two kinds of prospective situations

IIASA compares different prospective situations[27]. These prospective situations include:

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[26] A N% acidifying deposition gap closure means that, in each grid cell, we try to decrease by N% the gap between the depositions in 1990 and the level of the critical loads for which 98% of the ecosystems are protected.

[27] IIASA calls these prospective situations ‘scenarios’.

- emission levels and reduction costs by country and by pollutant;
- the exposition indicators that correspond to theses emissions levels, for each grid cell.

We can distinguish two main kinds of prospective situations:

- Situations without optimisation, calculated with the scenario analysis mode. The emission levels are set and the environmental expositions are deducted from them. E.g.: the scenario REF (business as usual for the activity and the emissions in 2010) and the scenario MFR, in which emissions are reduced as much as it is technically feasible.
- Situations with optimisation, derived from some 'optimal' emissions reduction strategies in 2010. These situations are calculated with the optimisation mode of the RAINS model, from some sets of optimisation constraints[28]. The module calculates at the same time the emissions and the effects indicators associated. E.g.: the scenario H1, on which the negotiations for the directive NEC were based.

4.1.2.2 The central scenario H1 (F1, K1)

4.1.2.2.1 General presentation

In its report to prepare the NEC directive (Amann et al., 1999a), IIASA gave the results of the RAINS optimisation module for different sets of optimisation constraints. The most important one is the central scenario (H1) that sets targets for gap closures equal in all the cells of the grid, compared to a reference year. Other scenarios modify slightly the targets of H1, or set constraints for only one criterion (only acidification for instance), or use different hypotheses (with or without Kyoto targets), etc.

H1 includes various targets:

- Reduction in 2010 of the area of unprotected ecosystems against acidification by at least 50% compared to 1990.
- Reduction of the population exposure to ozone (AOT60) by 2/3 between 1990 and 2010.
- Reduction of the ecosystem exposure to ozone (AOT40) by 1/3 between 1990 and 2010.

It does not include any target for eutrophication.

4.1.2.2.2 Examples of constraints for AOT60

As far as health exposure to ozone is concerned (AOT60), the environmental objectives are a complex set of different constraints:

1) The first constraint, called soft constraint.
   It aims at reducing the gap closure by 67%. In the strategies calculated by the optimisation module, in each grid cell, either AOT60 is reduced by at least 67% compared to AOT60 in 1990 or it remains at the 2010 reference level (situation REF), if the latter is lower.

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[28] IIASA calls these sets of environmental constraints 'scenarios' as well.

2) The compensation principle, aimed at averaging the efforts for each country.
   The previous constraint (soft constraint) for AOT60 is allowed to be exceeded in individual grid cells provided that the excess AOT60 (weighted by the population in these grid cells) should be balanced by over-attainments of the soft constraint in other grid cells within the same country (weighted by the population in these grid cells).
   This compensation is also possible across time: an over-accomplishment one year can balance an exceedance another year.[29]
3) Some more constraints to avoid some potential excesses due to the compensation principle:
   a) AOT60 has to remain below an absolute constraint (2.9 ppm.hours), except for the worst of the five considered years[30];
   b) AOT60 has to remain below the AOT60 of the reference situation for the year 2010;
   c) AOT has to close a minimum gap of y%.
4) The sensitivity limit of the model is set at 0.4 ppm.hour. This has two consequences:
   a) the objectives to be reached cannot be inferior to 0.4 ppm.hour;
   b) reductions below 0.4 ppm.hour cannot be used in the compensation principle.

4.1.2.2.3 The constraints for the other effects

As far as AOT40 is concerned, the set of optimisation constraints is similar (with a reduction of AOT40 by 33% and an absolute constraint of 10.0 ppm.hours).

As far as acidification is concerned, objectives are simpler:

- a 95% gap closure for excess cumulated acidity;
- a 50% gap closure for the area of unprotected ecosystems.

The compensation principle is introduced as well: it allows the excess cumulated acidity target of individual grid cells to be exceeded (up to a specified limit) provided such exceedances are balanced by additional environmental improvements (more than meeting the target) at other grid cells within the same country.

4.2 A FEW GENERAL QUESTIONS ABOUT OPTIMISATION CONSTRAINTS

4.2.1 Prime importance of the optimisation constraints

The optimisation module is only a tool. The way it is used, especially the way the targets are set, is essential. Optimisation does not give the absolute best solution. It only gives the solution that answers best a precise question. Defining what is an optimal strategy has to be done before using the optimisation module and is a very delicate task.

When thinking about the environmental goals, one has to answer two kinds of questions:

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[29] The years we consider here are the five meteorological years: to take into account the fact that meteorological conditions have a strong influence on ozone formation, AOT60 is calculated with the meteorological conditions of five different years.

[30] The ‘worst year’ is the year whose meteorological conditions lead to the most important ozone formation.

1) Which goals do we want to achieve?
2) Can the real world model we use today design strategies to achieve these goals? Is it efficient and precise enough to answer adequately the questions it is asked?

Answering a few questions is necessary when defining the environmental objectives:

- Do we want the maximal reduction of the costs with a given environmental goal (this is the way it is presently done) or maximal reductions of the environmental impacts with a given budget?
- Are the different environmental effects equally important?
- Can we authorise some targets to be exceeded if attaining them is too expensive? If yes, to what extent can we authorise such exceedances?
- Do we set global or local environmental goals?
- Do we take into account some equity considerations (such as the repartition of abatement efforts or the repartition of the benefits) between countries? between sectors? between social groups?

4.2.2 Equity

From a political point of view, reducing the overall environmental impact or minimising costs is not enough to define ‘good’ strategies. Checking that the air pollution reduction strategies are fair enough is also necessary. But defining what equity means and applying this concept to define fair emission reduction strategies is very difficult.

4.2.2.1 Upstream or downstream?

It is possible to set some equity constraints at different steps of the modelling and decision process. We can give here the two extreme solutions:

- Setting the equity constraints in the first place, when defining the environmental constraints. This is the way it is presently done.
- Not setting any ex ante equity constraints; checking ex post that the obtained strategies are not too unfair; correcting them if this is so.[31]

4.2.2.2 Similar efforts or similar effects?

An emission reduction strategy has some benefits (improvement of the environment) and some costs (emission reduction costs). It is possible to look for an equitable balance for both of them.

A fair repartition of the costs can mean different things: equality of the abatement cost per emitted ton of pollutant (which corresponds more or less to the polluter pays principle), equality of the abatement cost per inhabitant, equality of the marginal abatement cost (if a country has already decreased its emissions a lot, its marginal abatement costs have

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[31] It is quite a common process to evaluate public policies, especially in the United States: at first the environmental effects and the global cost of an emission reduction strategy are studied and then decision-makers check that it has not negative distributive effects (for instance negative impacts more important for the low-revenue populations).

increased and it will have to make a less important abatement effort)[32], etc.

A fair repartition of the efforts can be expressed as an obligation of means: we can imagine using in every country the same abatement techniques.[33]

With the present optimisation mode, it has been chosen to look for a fair repartition of the benefits (in relative terms). There is not necessarily a fair repartition of the costs.

4.2.2.3 Equity between countries? Equity between grid cells?

Studying the impacts of emission reduction strategies on each European citizen is impossible. At what scale can we study equity? It may be necessary to do so at the country level. It is possible to make it at a finer scale. Now, equity is scrutinised by individual grid cell (50 km x 50 km). And in a second step, constraints are relaxed and globalised, only to a certain extent, at the country scale.

4.2.2.4 Some difficulties in taking equity concretely into account

Taking equity into account is quite difficult for several reasons:

- Defining equity or justice univocally is impossible.
- Integrating equity criteria in the optimisation process makes it more complex and less transparent.
- Equalising the efforts or the expected results leads to a bottom levelling: if we want every single grid cell to benefit from a given improvement, this improvement cannot be too stringent lest it should be impossible to attain in some grid cells.
- Integrating equity constraints increases the costs of the optimal strategies, as they are defined in RAINS, and prevents them to satisfy to global cost-efficiency criteria.[34]

Finding a better balance between the global rationality constraints on the one hand, and local issues and equity considerations on the other, than that presently adopted in RAINS is necessary, but difficult.

4.3 DISCUSSION ABOUT THE OPTIMISATION OBJECTIVES TO BE USED IN RAINS

Defining the sets of constraints that are used in the optimisation process is the keystone of the whole RAINS model (at least in the optimisation mode), as it is used now. Far from being a purely technical aspect, it is based on a few choices that have deep political implications.

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[32] A global minimisation of the costs, with given environmental targets expressed as emission reductions, would equalise the marginal abatement costs. If we minimise the costs with constraints expressed in terms of effects, there is equality of the marginal abatement costs, weighted by the impact of the emission reductions.

[33] Such an approach is similar to that of the directive IPPC with the BATs or that of the directives on the sulphur content of fuels or on the specific emissions of vehicles.

[34] We talk here of the costs and the ratios costs/advantages as they are defined and calculated by RAINS. The model neglects numerous costs (for instance the social costs).

4.3.1 Discussion of the present constraints

4.3.1.1 Principles

The present goal is that in each European region (practically in each cell of the EMEP grid), the different indicators considered would decrease by a given minimal percentage. The optimisation goals are based on the following principles:

- The RAINS optimisation module aims at *decreasing exposition indicators*.
- This decrease is set in *relative terms* (percentage of reduction of the gap between the business as usual situation and the long-term target). Some absolute levels to be reached are set also but are they are less difficult to attain.
- The module aims at decreasing these indicators by *at least* a given percentage (and not decreasing them as much as possible).
- This given minimum reduction percentage is *the same in every grid cell* (as far as possible).
- *Cost minimisation* is a supplementary criterion, once all the above mentioned criteria are respected.

Putting things in a different way, the constraints and the optimisation process, as they are used now, aim in the first place at reducing the pollution effects in the most polluted grid cells and not at reducing the overall effects. They set some minimal constraints to be respected (nearly) absolutely everywhere but do not aim at going further; they aim at reducing the effects down to a given level and not at reducing them as much as possible (even if these reductions below the threshold could be obtained at a very low cost)[35].

4.3.1.2 Three kind of considerations

Practically speaking, the environmental goals that are used now stem from the conjunction of three kinds of considerations:

- some environmental and health goals in a strict sense;
- some equity goals (equity in the effects, by geographical zone);
- some mathematical difficulties.

From some constraints by grid cell that are averaged, to a certain extent, by country, the process leads, through a whole set of mechanisms aimed at making the initial constraints less strict but not too lenient, to a stack of mathematical artefacts and to an extremely complex set of optimisation constraints, even though each one, taken individually, can perfectly be justified.

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[35] In a way, because of the compensation mechanism, the module sometimes aims at reducing expositions below the threshold in a few grid cells to balance for exceedances in other grid cells.

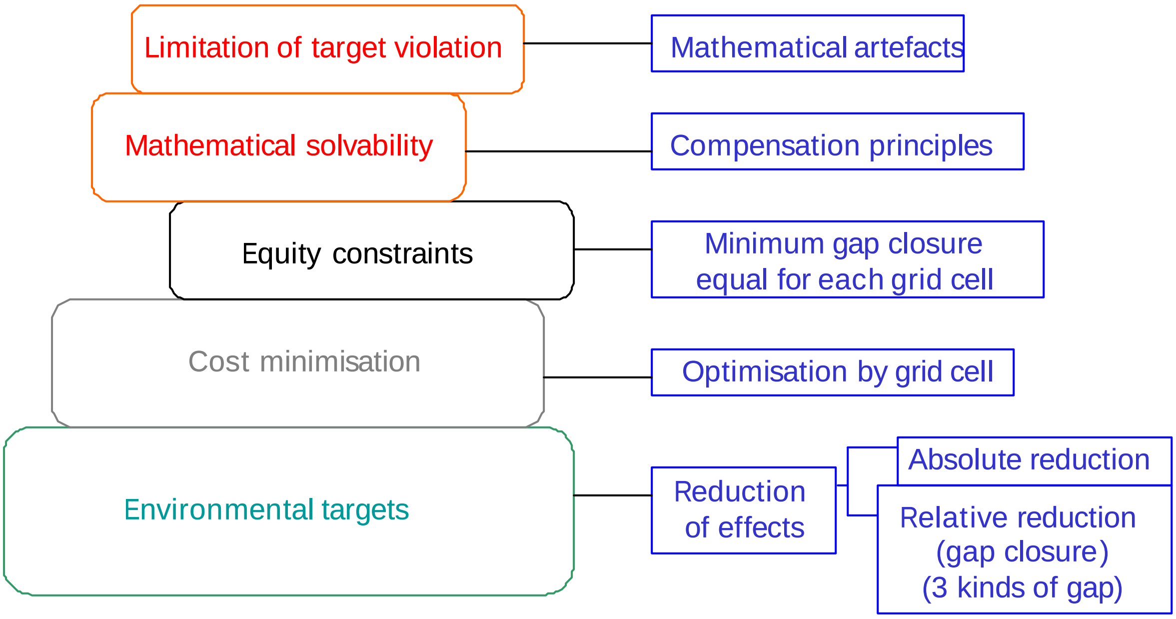

Figure 5. The different kinds of considerations that lead to the definition of the constraints in the optimisation module of the RAINS model

4.3.1.3 Induced complexity

The complexity of the optimisation module stems from different sources. Some of them seem unavoidable, as they are due to the intrinsic complexity of the issues at stake: non-linearity of some phenomena (ozone formation), growing number of pollutants and of effects, etc.

But one of the main sources of complexity of the optimisation module, defining optimisation constraints for each grid cell, could quite easily be avoided. Compared with an optimisation by country, the optimisation grid cell increases greatly the number of constraints (more than 5,000 grid cells against only 41 countries). Furthermore it leads to some mathematical issues that made necessary the use of some mathematical artefacts (compensation principle, authorised violation of environmental targets). All this greatly increases the complexity of the model and the time necessary to perform a model run. Besides the mathematical artefacts, due to their complexity, are not very transparent.

4.3.2 Alternative optimisation scenarios

In 1998, IIASA studied for the French Ministry of Environment three alternative scenarios (Landrieu et al., 2000; Amann et al., 2000b).[36] These three scenarios are simpler and they set environmental goals at a more global scale than those studied by IIASA. Two of them are optimisation based. At the European level, they yield better benefits/costs results. This is because they do not comply with all the environmental constraints of the IIASA scenarios: IIASA assumes that some particularly sensitive grid cells will be better protected with its own scenarios.[37] The alternative scenarios aim at maximising the global improvement instead of setting objectives that have to be reached everywhere. But they

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[36] For more detail, see the appendix A, ‘A few alternative scenarios’.

[37] It is the case at least theoretically, in the results of the model. But in the real world, the results are plagued with so much uncertainty that it is maybe worthless to deal with so precise goals.

have the advantage to define some emission reduction policies that are simpler to put into practice, and thereby more easily enforceable and less expensive.

The IIASA scenarios, and especially the constraint by grid cell, would enable to obtain strategies that would reduce the effects in all the grid cells more homogeneously. But even this is not to taken for granted. We compare in the appendix, two optimisation-based scenarios with equivalent global environmental targets:

- a scenario with global constraints, J14; it sets environmental targets for Europe as a whole instead of targets for each grid cell (with a compensation by country);
- a scenario with constraints by grid cell, G5/1;

By comparing them, we can notice the following elements:

- The global scenario, J14, is less expensive than G5/1 (41% less).
- Globally the scenario J14 leads to a better protection of the environment and human health than G5/1, for the four criteria considered (AOT40, AOT60, acidification and eutrophication).
- As far as acidification and eutrophication are concerned, some countries are more protected with the scenario with constraints by grid cell (G5/1), some others are less protected; the most polluted grid cells are better protected with the scenario with constraints by grid cell (G5/1).
- But as far as exposure to ozone (human health and vegetation exposures to ozone) is concerned, all 15 European countries are more protected with the global scenario (J14) and the majority of the grid cells, especially the most polluted ones, are more protected with the global scenario.

This global scenario has also the advantage to be defined in a simpler way, therefore leading to optimisation processes less complex and more transparent.

4.3.3 Conclusion on optimisation constraints and suggested developments

Ideally, taking equity into consideration, defining environmental and health constraints at a sub-national scale are very important issues to consider. But does the integrated modelling state of the art allows dealing with these issues in a satisfactory way? Reviewing the RAINS model, it is very important to wonder whether it is precise enough to deal with local issues (i.e. in 50 km x 50 km grid cells), whether the constraints, as they are formulated now, achieve their theoretical goals (reduction of the effects for everyone) far better than some global, far simpler, constraints. Furthermore, is it useful to have a very precise model if the input data suffer from important uncertainties? As we have seen in the second part, the uncertainties on the input data, and especially on the emission inventories, are quite important. They may be more important than estimated by IIASA. Furthermore the optimisation results are quite sensitive to the variation of the input data. So is it sensible to try to define very precise optimisation results, such as national emission ceilings derived from constraints set for each single grid cell, since we know the uncertainties about the emissions are very important? A balance has to be reached between the preciseness of the optimisation constraints and the robustness of the results.

As we have seen, the present sets of optimisation constraints are very complex. They will become even more complex with the integration of new pollutants and new effects in the

RAINS model. Using simpler sets would enable to make the optimisation process more efficient and more transparent. Besides using simpler optimisation constraints can make the integration of the target violation minimisation term in the goal function useless. Hence, it would enable to simplify the mathematical equations of the optimisation module, thereby making it more robust.

Furthermore from the study of the alternative, 'global', optimisation scenario in the previous paragraph, it can be inferred that defining some scenarios that lead to less expensive strategies, with better global environmental results for all the criteria and with better environmental results by grid cell for some of the criteria is possible.

We can give several alternative sets of optimisation constraints:

- Minimise costs by setting constraints globally and not for each grid cell.
- Minimise costs by setting constraints by country.
- Set costs and minimise the population exposure to ozone and/or to particulate matter (see appendix C, 'Setting environmental goals or setting costs?', for more detail).

CONCLUSION

The RAINS model suffers from several drawbacks and limitations. They are, to a great extent, unavoidable since the issues to be modelled are very complex. Moreover, they do not prevent the model from giving useful and interesting results.

The scenario analysis mode, notwithstanding its great uncertainties, can deliver very helpful information on very complex issues.

The optimisation mode can also potentially shed useful insight on the issues at stake. It can help define emission reduction strategies that reduce the global emission abatement costs and maximise positive effects on health and the environment. Nevertheless, the way this mode is used, and especially the definition of the optimisation constraints, suffers from defects that reduce the robustness and the transparency of its results.

The RAINS model and its optimisation module could be used in a wide range of different ways. Unfortunately the optimisation mode is now exploited only to define national emission ceilings derived from environmental constraints set for each grid cell. Yet, establishing other kinds of emission reduction strategy and running the optimisation module with simpler environmental constraints than those used now is possible and could bring helpful complementary information.

This model was initially developed to deal with a mono-pollutant and mono-effect problem (sulphur dioxide and acidification). In this relatively simple framework defining quite complicated optimisation constraints was probably adequate. But since then, the growing complexity of the issues to be modelled has been leading to a piling of heterogeneous elements in the optimisation constraints. Now they are derived from four heterogeneous kinds of drivers: environmental targets, equity constraints, cost minimisation objectives and mathematical solvability issues. Mathematical artefacts can partly determine the optimisation results but they are not made explicit, therefore making the process quite obscure. It is of the utmost importance, as the RAINS model is undergoing deep modifications, to rethink the definition of the environmental constraints and to make them simpler so that they could be more easily understandable by decision-makers and stakeholders. Defining simpler and more various environmental constraints could help the model deliver more transparent and, in many cases, more robust, results.

We can summarise here some of the possible ways forward suggested in this report:

- Increase the transparency about the RAINS model and its utilisation.
- Introduce only the emission reduction costs in the goal function of the optimisation module. This implies suppressing the term aimed at minimising the environmental target violation.
- Use simple and transparent optimisation scenarios. Run the optimisation module with various optimisation scenarios of this kind to give several views of the same issue.

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LIST OF APPENDICES

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APPENDIX A. A FEW ALTERNATIVE SCENARIOS

In 1998, the French Ministry of Environment commissioned IIASA to study three alternative scenarios (Amann et al., 2000b; Landrieu et al., 2000).

A.1 GLOBAL CONSTRAINTS

A.1.1 Global comparison

The first scenario studied, J14, sets environmental goals for Europe as a whole instead of goals for each grid cell (with compensation by country). Comparing it with the scenario G5/1 (which sets the same level of constraints as J14 but for each country) gives the following results:

- the total cost of J14 is much lower than that of G5/1 (41% lower);
- for each of the four criteria (acidification, eutrophication, human exposure to ozone and vegetation exposure to ozone), the global protection level is between 7% and 11% higher with J14 than with G5/1.

A.1.2 Cell by cell comparison

If the scenario G5/1 is much more costly, it is due to the constraint by grid cell. This means that the scenario J14 is prone to leave aside some particularly polluted grid cells. We have studied this hypothesis with the RAINS model available on the Internet.[38]

For average AOT60 (expressed as person.ppm.hours), global exposition is 9% lower with J14. Furthermore exposition is lower in 81% of the grid cells. Besides in all the most polluted grid cells (that is those where average exposition is superior to 1.5 ppm.hour, 2.8% of the total number of grid cells), exposition is lower with J14. Therefore J14 is more efficient with ‘hot spots’ than G5/1 and it reduces more the inequalities in exposition.

For AOT40 (expressed as km^2.ppm.hours), global exposition is 11% lower with J14. Furthermore exposition is lower in 83% of the grid cells. And for 39 out of the 42 most polluted grid cells, the situation is better with J14.

For acidification, J14 enables to protect an area 10% greater than G5/1. But G5/1 gives a better protection to the most polluted grid cells.

For eutrophication, J14 enables to protect an area 7% greater than G5/1. But G5/1 gives a better protection to the most polluted grid cells.

A.1.3 Conclusion

The comparison of the emission reduction strategies derived from the scenarios J14 and G5/1 gives the following results:

- J14 is less expensive than G5/1 (41% less);

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[38] This study was conducted with the version of the RAINS model that was available online on April 11th 2003.

- globally, J14 leads to a better protection of environment and human health than G5/1, for the four criteria considered;
- for two out of four criteria (human health and vegetation exposures to ozone), J14 leads to greater excess reductions in the most sensitive (i.e. the most severely affected) grid cells than G5/1.

A.2 GROWING COST EMISSION REDUCTION MEASURES

In the second scenario studied (J15 or 'robust scenario'), the cost of emission reduction policies is set (it is set equal to that of the strategy derived from the central scenario J1) and the emission reduction measures are just piled up, from the less expensive ones (that is those with the lowest marginal abatement cost) to the more expensive ones. "For each pollutant separately it is assumed that emission control measures are taken in order of their marginal costs starting from the cheapest until the relevant J1 costs have been reached" (Amann et al., 2000b). So in such a strategy, all the European countries undertake all the measures whose marginal cost is inferior to a given level.

By definition, the global costs of J1 and that of J15 are equal. The areas of protected ecosystems against acidification and eutrophication are 11% and 38% higher with J15 than with J1; the reduction of vegetation exposure to ozone (ppm.hours in excess weighted by the considered area) is 8% higher; on the other hand the reduction of health exposure to ozone (ppm.hours in excess weighted by the considered population) is 21% lower.

So, with the same cost, the 'robust' scenario J15 gives better results than J1 for three out of four criteria, as far as the global protection at the European level is concerned.

A.3 REDUCTION OF THE EMISSIONS PER CAPITA

A third scenario (H13) aims at reducing, in each country, the emissions per capita to get as close as possible to those of the country for which they are lowest. Comparing its advantages/costs ratios for each of the four criteria with those of an IIASA scenario (H2), we can see that the H13 ratios are higher than the H2 ratios for all the criteria. The H13 advantages/costs ratio is 4% higher than that of H2 for the human health exposure to ozone and it is 250% higher for the ecosystems area protected against eutrophication.

A.4 CONCLUSION

What can be concluded from these comparisons? These three scenarios are simpler and they set environmental goals at a more global scale than those studied by IIASA. At the European level, they give better benefits/costs results. This is because they do not comply with all the environmental constraints of the IIASA scenarios: some particularly sensitive grid cells will be better protected with the scenarios of IIASA. (It is the case at least theoretically, in the results of the model. But in the real world, the results are plagued with so much uncertainty that it is maybe worthless to deal with so precise goals.) They aim at maximising the global improvement instead of setting objectives that have to be reached everywhere. But they have the advantage to define some emission reduction policies that are simpler to put into practice, and thereby less expensive (as far as transaction costs are concerned and this kind of costs is not taken into account in RAINS).

APPENDIX B. A VERY SIMPLE OPTIMISATION PROBLEM

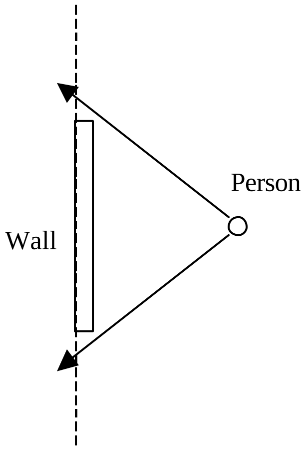

Figure 6. Modelled problem

Let us consider the following problem: somebody wants to tread over the dotted line as quickly as possible, without getting into the wall.

We know the person's speed and the distance between him and the line. The only decision variable is the departure angle.

We can imagine a very simple scenario and optimisation model:

- In scenario analysis mode, we give the model the initial position and the departure angle; it gives us the time after which the person treads over the line and whether he gets into the wall or not.
- In optimisation mode, the model minimises the time to tread over the line while complying with the constraint 'not to get into the wall'. We give it the initial position and it gives us the optimal departure angle and the time after which the person treads over the line.

If we conduct a sensibility analysis with these two modes, we get the following results:

- In the scenario analysis mode, an uncertainty with the departure angle or with the initial position leads to an uncertainty of quite the same magnitude with the calculated time.
- But in the optimisation mode, a slight uncertainty with the initial position can lead to two strategies completely different ('go to the left of the wall' or 'go to the right of the wall').

Two things have to be pointed out:

- This unstability is intrinsic to the problem to be resolved and does not reveal at all a shortfall of the optimisation process.
- Both solutions ('go to the left of the wall' or 'go to the right of the wall') can produce nearly the same results but a 'middle' choice between the two of them, i.e. taking the golden medium ('go straight in the middle') is not an optimal solution any longer, not even a good one since the constraint 'not to get into the wall' is not respected.

The same kinds of remarks can be made about the RAINS model:

- The model giving unstable solutions is not a hint that it does not work properly.
- If different sets of input data give different optimal solutions, a 'golden medium' between them is not necessarily another optimal solution, not even a good one…

APPENDIX C. SETTING ENVIRONMENTAL GOALS OR SETTING COSTS?

Theoretically, optimisation enables to minimise costs with a given environmental constraints (which is usually done by IIASA) or to maximise environmental benefits with a given budget or with given abatement costs.[39]

The advantage of the latter method is that it aims at reducing pollution as much as possible, whereas with the former it only aims at reaching given levels of pollution and not at over-complying, even if the cost to do so is quite low.

The first methodology is particularly justified when the process aims at reaching some well defined thresholds (for instance thresholds above which it is considered that risks are not acceptable any more). It is now the case for the constraints that set a ceiling for the exposure to ozone (for instance in H1, AOT60 has to stay below an absolute constraint set at 2.9 pmm.hours). On the other hand, it is not the case for the constraints expressed as gap closures: they are based on relative amelioration considerations and do not have any well-defined objective physical characteristics.

An important advantage of the first methodology is avoiding setting ex ante weighting between the different effects.[40] On the contrary, if we want to maximise environmental improvements with a given budget, it is necessary to strike some balance between these effects (which means for instance that avoiding N deaths by reducing the ozone concentrations is worth the same as protecting M hectares against acidification).

IIASA justifies its choice in one of its latest report: “Early experiments with RAINS explored the practical usefulness of alternative optimisations (…), e.g., minimized environmental impacts for a total budget constraint. Other integrated assessment models, e.g., the Imperial College’s ASAM model (…) tested further concepts. Consultations with decision makers, however, led to the conclusion that the cost-effectiveness principle, materialized through the cost minimizing optimisation as implemented in RAINS, met best the needs of the actual setting of international environmental policy in Europe” (Amann et al., 2004). But would not it be possible to minimise environmental impacts for a total budget constraint to conduct some sensitivity analyses?

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[39] According to IIASA, the second approach (i.e. “optimise the set of emission control measures to be taken for a given cost”) “is not currently possible with the present version of the RAINS model” (Amann et al., 2000b).

[40] Nevertheless such a weighting of costs of different environmental criteria is introduced when a term to minimise the environmental constraint violation is introduced in the goal function.