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# Exceedence, Damage and Area Minimisation Approaches to Integrated Acidic Deposition Modelling

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**Abstract**

Optimisation procedures used in abatement strategy models have made use of the relaxation of targets if feasible solutions cannot be found. However, exceedence, damage and area minimisation approaches provide alternative options. This paper explains and demonstrates how these approaches can be used to develop acidic deposition abatement strategies in Europe. The Co-ordinated Abatement Strategy Model (CASM) structure and input data are described and results for the alternative optimisation procedures are presented. The paper concludes with a discussion of the advantages of the different options available for developing cost-effective abatement strategies.

## 1. INTRODUCTION

Acidification of terrestrial and aquatic ecosystems is recognised as one of Europe's most significant international environmental problems. It is accepted that a major cause of this ecological damage is the transboundary atmospheric transport of certain gaseous pollutants - oxides of sulphur and nitrogen ($SO_x$ and $NO_x$) and reduced nitrogen ($NH_x$). The main sources of $SO_x$ and $NO_x$ are processes involving the combustion of fossil fuels, whilst $NH_x$ is released predominantly from agricultural sources. The United Nations Economic Commission for Europe (UN-ECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) has recognised this problem in the Helsinki and Sofia Protocols which specify flat rate reduction levels for emissions of $SO_2$ and $NO_x$ respectively, for each Party to the Protocol. In June 1994, the Oslo Protocol on further reductions of sulphur emissions (UN-ECE, 1994) was signed and this marked a significant change in approach. This Protocol differentiates national emission reduction obligations according to the relative harm emissions cause and the relative cost of controlling emissions. Integrated assessment models have played a key role in this process by providing optimised abatement strategies from which the final policy has been negotiated.

Three models have provided analyses of abatement strategies to the UN-ECE Task Force on Integrated Assessment Modelling (UN-ECE, 1993). These are: ASAM (ApSimon and Warren, 1992), RAINS (Alcamo *et al.*, 1990) and CASM (Gough *et al.*, 1994) Each utilises input data specifying emissions, abatement costs, atmospheric transport and deposition targets based on critical loads but the models differ in their mode of operation. The CASM model, detailed here, was developed by the Stockholm Environment Institute and uses linear programming optimisation techniques to generate cost-effective, environmentally targeted strategies; its main strength lies in its flexibility and the choice of optimisation approaches that it offers.

## 2. CO-ORDINATED ABATEMENT STRATEGY MODEL

CASM is shown diagrammatically in Figure 1. The input data requirements include base case quantities of emissions, abatement cost curves for emissions sources, air transfer coefficients, receptor sensitivity data, and problem definition specifications. Calculations have been restricted to analysis of the abatement of sulphur dioxide emissions for the work for the Oslo Protocol; future developments will extend the model to include other long-range transboundary air pollutants.

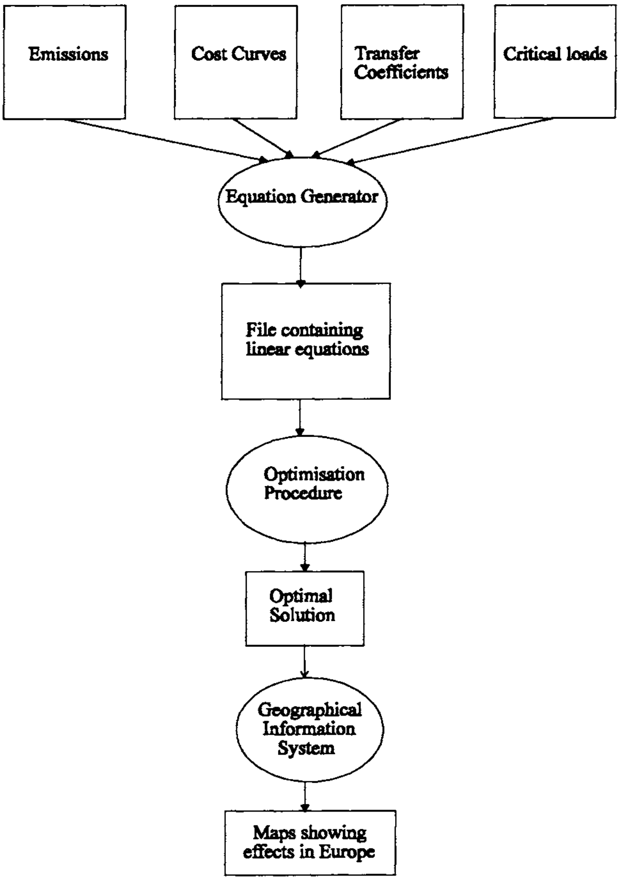

Figure 1. CASM flow diagram.

Estimates of emissions for the target year (in this case, 2000) are made from projected energy balances for each of 35 source regions. Marginal abatement cost curves are produced using a detailed database of point sources in conjunction with the energy forecasts and national cost data. These specify estimates of annual abatement costs of different options of sulphur removal. They consist of cost steps in order of increasing marginal cost and only describe costs for combinations of "bolt-on" technologies. The assumption behind the use of these cost curves is that abatement measures will be applied in least cost order and without structural changes in a region's energy consumption. One reason behind this last assumption is that official energy forecasts are used; any provision for fuel switching or energy efficiency measures should be taken into account as part of these energy balances. It is also likely that such changes would be motivated by reasons other than sulphur abatement for acidification (for example, control of greenhouse gas emissions) and to allocate costs becomes complex. In order to consider such measures the use of specific energy scenarios are generally involved; these incorporate these issues and may still be used in conjunction with abatement cost curves.

Atmospheric transfer coefficients have been taken from the EMEP model (Iversen *et al.*, 1989, 1991) which provides estimates of annual deposition from each source region across a European grid of 150 km by 150 km (the EMEP grid). Critical loads applied to the SEI map of relative sensitivity of ecosystems to acid deposition have been used (Chadwick and Kuylenstierna, 1990). Atmospheric deposition of base cations has a neutralising effect on acidic deposition and a methodology for estimating this contribution for each EMEP grid square has been developed. With the exception of the EMEP data, all data used to generate the results presented in this paper in the model have been prepared by SEI but data from other sources (for example "official" data) may be used in CASM.

There are two broad categories of approaches for deriving abatement strategies; they may be source-based (non-targeted approaches) or receptor-based (targeted approaches). Non-targeted approaches take emission standards, reduction levels or other emission source constraints and find the least-cost solution; these approaches do not incorporate environmental constraints. Targeted approaches, however, aim for a least-cost solution but include deposition constraints which may be based on the sensitivity of the environment to acidic deposition. Thus the destination and relative effects of a source's emissions are taken into account in the optimisation procedure. The optimisation problems discussed here are developed as sets of equations which can be solved using linear or integer programming techniques. In each case, there is one "objective function" (e.g., to minimise the total cost of abatement, or to minimise the deposition in excess of target loads) that is optimised subject to various "constraints" (e.g., that the deposition in a particular receptor cannot exceed a specified value). Linear Programming (LP) is a methodology for expressing problems in a series of linear equations and then finding a solution that optimises (maximises or minimises) the specified objective. The restriction of the problem formulation to linear equations ensures that one can always find the best solution - if any solution does exist. The algorithm for finding the best solution is known as the Simplex Method (see Walsh, 1971; Williams, 1985) and is implemented in the CASM model with a commercial package called LINDO (Schrage, 1989).

## 3. APPROACHES TO DEVELOPING ABATEMENT STRATEGIES

The Oslo Protocol is different from the Helsinki and Sofia Protocols since it has aimed to incorporate the relative environmental implications of European abatement strategies and has been developed using information provided by optimisation models. This marks a change from the earlier, source-based, approaches which adopted uniform emission cutbacks in all countries.

Strategies in which emission levels are specified initially may be investigated using the CASM model, which provides information concerning the cost and environmental performance of the strategy. However, the main advantage of this model is that it provides a decision maker with a choice of policy goals (objectives) upon which to optimise. The types of objective that may be considered and how these are implemented in the model are discussed here. The difference between the approaches lies in the choice of objective function - the attribute of the strategy to be minimised. The way the problems are formulated using the abatement cost curves ensures that the most cost-effective solution will always be found, such that, even if cost does not form the objective function, there will not be an alternative solution that would achieve the same level of the objective for a lower cost than the final solution. The approaches available are described and these cover the range between source-based approaches and receptor-based approaches.

### (i) Uniform Percentage Reductions (UPR)

This is the type of approach adopted by the Helsinki Protocol in which each source region reduces its emissions by a fixed percentage relative to a base year. It is a source-based approach and does not involve optimisation techniques. CASM may be used to estimate the costs of implementing this type of strategy and to simulate the resulting deposition pattern in Europe.

### (ii) Emissions Minimisation

This is a source-based approach and incorporates no information concerning the destination of emissions or the environmental status of receptors. It simply ensures that the maximum amount of abatement is achieved in Europe for a given cost. Directing abatement to areas where it can be achieved most economically does not necessarily ensure that the most harmful emissions are reduced.

### (iii) Targeted Cost Minimisation

In this case the objective is to minimise the total cost of abatement, whilst meeting deposition targets at the receptors. This approach is attractive in that it provides for sustainable levels of deposition at all receptor locations, but some drawbacks must be recognised. Most importantly, for actual data sets, where deposition targets are set at scientifically determined critical loads and emissions reductions cannot be entirely eliminated, one may find that it is not technically feasible to meet all receptor targets, i.e. even after all of the “available” abatement is implemented one or more receptors continue to receive deposition in excess of the critical load. If this is the case, then the analyst may decide to loosen some, or all, of the receptor targets, or to provide for higher levels of abatement through changes in the energy system.

An example of a targeted cost minimisation approach where the receptor targets have been relaxed from the critical load value is the Gap Closure approach (UN-ECE, 1993). In this approach the receptor targets are relaxed to a fixed reduction point between present deposition levels and the critical load (for example, 60 per cent). The Oslo Protocol was based on results from a 60 per cent Gap Closure between 1990 deposition levels and 5 percentile critical loads (the 5 percentile critical load is the value that ensures the protection of at least 95 per cent of the area of an EMEP grid square); if current deposition is below the critical load no modification is required.

This approach constitutes a stage between source-based strategies and optimised receptor-based strategies. Although the solution is driven by receptor targets based on critical loads, these targets are governed by additional factors to the environmental sensitivity of a receptor, for example, the Gap Closure targets are influenced by the level of abatement already in place in some countries. In any receptor, exceedence will be reduced beyond the 60 per cent target only as a by-product of achieving neighbouring targets; there is no pressure on the model to go beyond the specified targets. Gap Closure provides a useful means of defining intermediate targets externally to the optimisation process.

### (iv)Exceedence Minimisation

Exceedence minimisation is a receptor-based optimisation approach. There is no requirement for environmental targets to be modified if they cannot be achieved - critical loads may be used. The model reduces the total exceedence in Europe to the smallest amount achievable within a given total cost. Receptor sensitivity may be described by single square values (e.g. the 5 percentile) or deposition may be compared to an area weighted distribution of classes of critical loads (the "subsquare approach"). In LP terms this is a goal programming approach (Nijkamp, 1980; Williams, 1985), which is a technique used for solving problems allowing the relaxation of certain constraints (in this case the achievement of critical loads). The amount by which these constraints are violated is minimised, for example, critical load exceedence. Goal programming techniques have been used in the development of abatement strategies for control of acid deposition in the past by Ellis (1988). Ellis's aim was to determine opportunities for cost savings through the relaxation of deposition targets given a level of uncertainty associated with the atmospheric transfer models.

Exceedence Minimisation adopts the assumption that ecosystem damage is proportional to critical load exceedence. The definition of critical loads does not specify the shape of the response of a receptor in excess, but there is empirical evidence that damage to ecosystems is related to exceedence of critical loads. Several studies have documented instances of acidification in Europe (GEMS, 1988-1991; Kuylenstierna, 1993; Rosseland and Henriksen, 1990) and comparisons of data from these studies with modelled exceedence for these locations have revealed correlations between damage and exceedence (Kuylenstierna, 1993). Minimising the total exceedence in Europe subject to a total cost constraint generates a strategy that brings deposition as close as possible to the goal of reaching critical loads throughout Europe. Statements concerning the shape of such a dose-response function should be treated with caution at this stage, but existing research does not rule out the exceedence model of damage, illustrated in Figure 2.

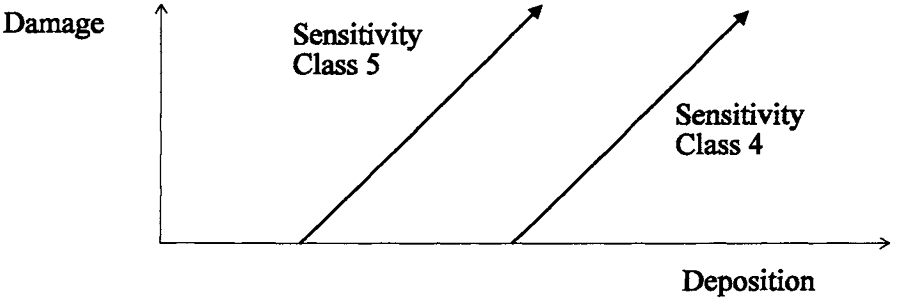

Figure 2. Damage function used in Exceedence Minimisation.

### (v) Damage Minimisation

Exceedence Minimisation considers all receptors to be equal, in terms of the potential damage expected from a unit of exceedence. It is possible to differentiate between receptors by applying weights to different classes of sensitivity and hence prioritise reductions in exceedence over, for example, more sensitive receptors. Another way of viewing this is to consider that these receptor-based models incorporate different types of damage function. Exceedence Minimisation assumes a linear damage function of equal slope across all receptors. Damage Minimisation assumes a linear response with different slopes for different critical loads or receptors, shown in Figure 3. The objective of this approach is to minimise the total weighted exceedence in Europe, where the weights describe the slopes of the damage function. Although at present there is insufficient evidence to suggest that this is an accurate model of ecosystem response, the method may still be useful for exploring the implications of prioritising the protection of certain areas and to accommodate developments in dose response analysis. These receptor-based approaches are expressed in terms of assumed damage responses; in this sense the Gap Closure optimisation does not conveniently fit into this type of analogy.

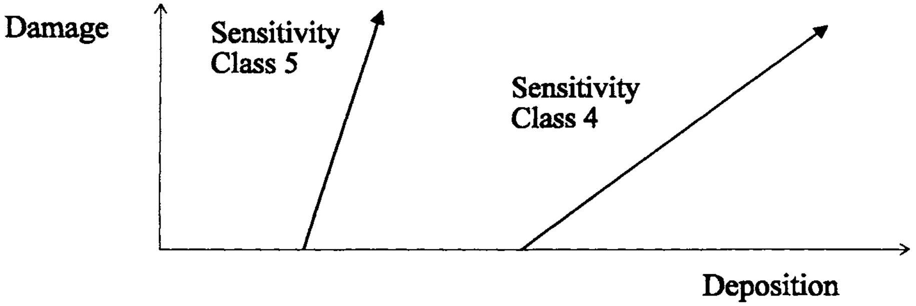

Figure 3. Damage function used in Damage Minimisation.

### (v) Area Minimisation

Assuming deposition is not expected to be reduced to below critical loads in every receptor, this approach could be seen as a literal interpretation of the definition of critical loads. The objective is to minimise the area over which critical loads are exceeded; abatement is prioritised at sources through which deposition can be reduced to below critical loads. The assumption behind this approach is that once the critical load has been exceeded there will be no benefit to an ecosystem of limiting any excess deposition. This model of dose response is illustrated in Figure 4.

Area Minimisation introduces a new type of formulation, requiring a different solution technique. In standard linear programming, the variables can take on any value in the continuous range from zero to their specified upper limits. With Integer Programming (IP), some of the variables are permitted to have only integer values in the solution. This is especially desirable if a variable represents a discrete countable number of some entity, such as number of receptors exceeded. This additional requirement greatly complicates the solution process, since the Simplex Method can no longer be relied upon to find the optimal solution. The number of potential solutions for an

IP can be very large and difficult to solve. A number of algorithms have been developed to solve these problems in a reasonable time. The most common method used for Integer Problems is called the "Branch and Bound" (B&B) technique (Williams, 1985); this method is used in CASM (Schrage, 1989). Although the B&B technique is much more efficient than simply enumerating the possible solutions, it is still much more computationally expensive than the solution of an LP using the Simplex Method.

On further consideration this may not appear to be such an appropriate method. It may be very costly to implement small reductions necessary to reach critical loads in some receptors when, for the same cost, large reductions in exceedence could be made elsewhere. This places a great emphasis on the certainty of both the critical load values and deposition estimates; the model solution would be highly sensitive to changes in these values. The concentration on achieving critical loads in some areas may also result in areas of extremely high exceedence, i.e. in those locations where critical loads are infeasible targets, no effort will be placed on reducing deposition.

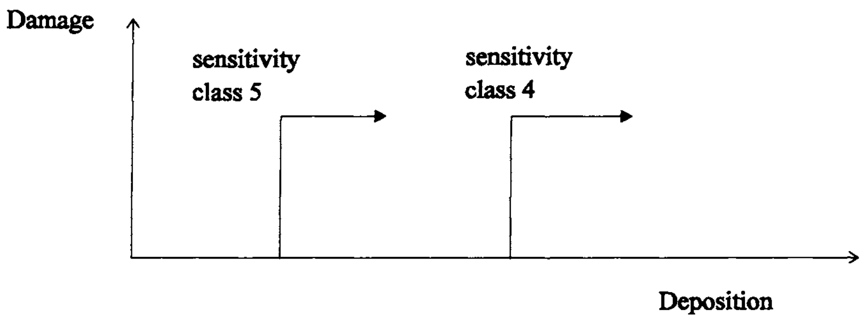

Figure 4. Damage function used in Area Minimisation.

## 4. COMPARING THE PERFORMANCE OF OPTIMISED STRATEGIES

Results from the CASM model are presented for the approaches listed above to illustrate the implications to the abatement strategies they derive. These have all been implemented using SEI data wherever possible, including the critical loads data. These results are presented to provide an indication of the consequences of adopting these approaches; since they have not been calculated using official data, they differ from those results presented to the UN-ECE for work within the Convention and should not be compared directly with similar results in other documents. Each type of run has been analysed across a range of abatement levels. The initial point of comparison has been a series of uniform reduction levels [approach type (i)]; the total cost estimated by the model for implementing these strategies have subsequently been used as budget constraints where one is required [approaches (iv), (v) and (vi)]. Two targeted cost minimisation [approach (iii)] results are presented for targets set to 50 and 60 per cent Gap Closure levels.

The two most commonly used criteria for assessing the environmental performance of abatement strategies are total excess of critical loads and area of critical load exceedence. Plots of these indicators against total annual cost of implementation are presented in Figures 5 and 6, which illustrate European totals for the entire range of runs carried out. The presentation of the results over the two different evaluation criteria (amount and area of critical load exceedence) demonstrates how the choice of strategy will change according to the policy goal used in the model. The benefits, in these terms, of adopting an optimised targeted approach over a source-based approach are immediately apparent. In Figure 5, as the strategy has been defined on this basis, Exceedence Minimisation clearly offers the most efficient solution if reducing exceedence is taken as a policy goal; similarly, in Figure 6, Area Minimisation provides the solution leading to the smallest area of exceedence. The position of the third approach, targeted cost minimisation (Gap Closure), should also be noted. In both Figures these strategies lie on the "upper" edge of the targeted strategies, between the receptor-based and source based approaches. The graphs illustrate that, for a given expenditure, there are great benefits in terms of environmental protection to be gained through taking an optimised targeted approach. As the total cost of these strategies increases, i.e. as more sources approach their maximum feasible reductions, these lines begin to converge. This happens as there become fewer alternatives for locating emission reductions.

The implications for critical load exceedence under these strategies may be seen more clearly in the maps shown in Figures 7 to 9. These also give an indication of the differences in the amount of exceedence in the different regions. The improvement, in terms of reduced exceedence, gained by adopting a targeted approach is obvious. The advantage of Exceedence Minimisation over Gap Closure shows up on these maps in the Kola Peninsular, Bulgaria, the Alps, Spain and the UK; these benefits are reflected in the level of effort required in these regions.

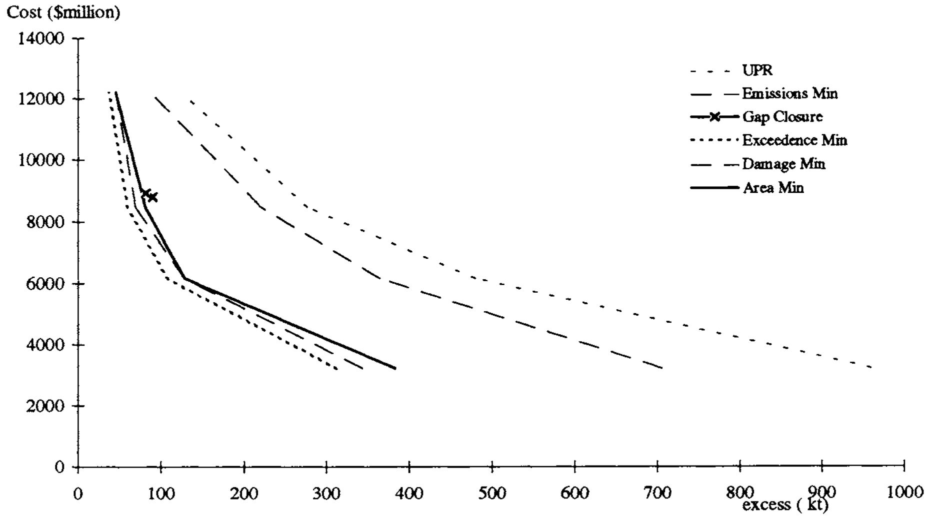

Figure 5. Summary of model results.

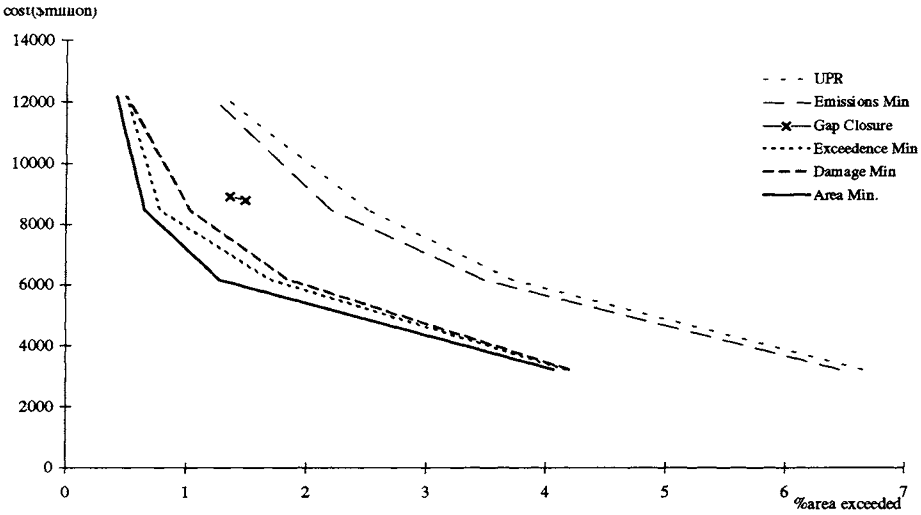

Figure 6. Summary of model results.

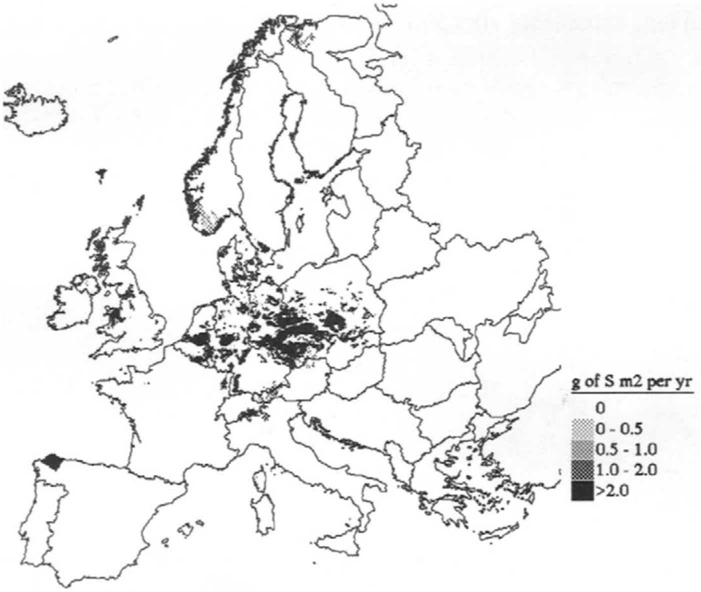

Figure 7. Critical load exceedence after 60% Uniform Percentage Reductions.

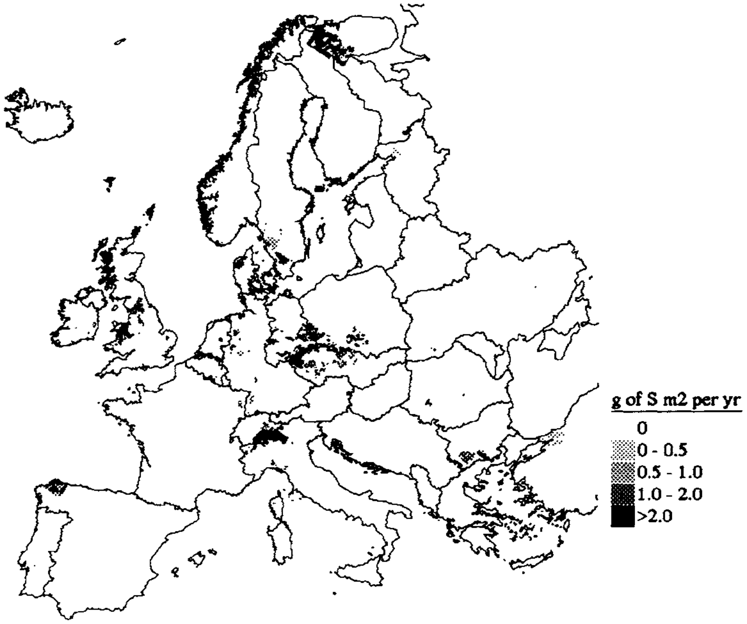

Figure 8. Critical load exceedence after 50% Gap Closure.

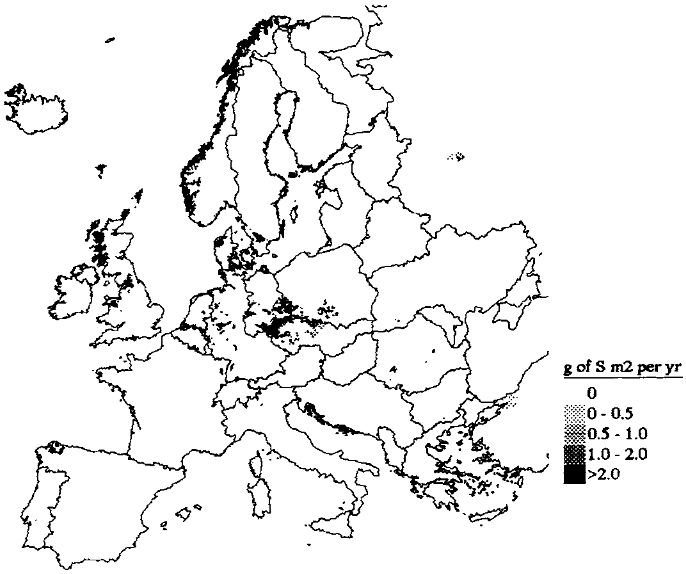

Figure 9. Critical load exceedence after Exceedence Minimization.

## 5. DISCUSSION

The examples of model runs presented in this paper have shown the potential for developing cost effective abatement strategies using optimisation models. These can achieve significant improvements in the environmental effectiveness of a strategy for equivalent levels of expenditure in Europe. The most efficient of these approaches are those that take a receptor-based approach and derive cost effective solutions according to different environmental policy goals.

However, the notion of efficiency here applies to considering Europe as a whole. The intermediate to such approaches, Gap Closure, has the advantage that the proportional reductions in exceedence are equal in every country. This does not necessarily guarantee that the environmental protection in every country will be equal or that there are not other strategies that benefit more regions. These issues arise because there is no straightforward solution to the acid rain problem in Europe with different relative sensitivity of environments, and non-uniform mixing and transport of pollutants across national boundaries. It has been shown that integrated models can provide the decision maker with valuable information to enable the best to be gained from international policy. Before a single approach is adopted the decision maker must decide exactly what the aim of the strategy is, what it is to achieve and how the benefits are to be assessed.

## 6. REFERENCES

1 UN-ECE, Protocol to the 1979 Convention on Long-range Transboundary Air Pollution on Further Reduction of Sulphur Emissions. United Nations Economic Commission for Europe. ECE/EB.AIR/40 (1994).

2 UN-ECE, State of Transboundary Air Pollution: 1992 Update. Air Pollution Studies Number 9. ECE/EB.AIR/34. United Nations Economic Commission for Europe, Geneva (1993).

3 H.M. ApSimon and R.F. Warren, Abatement strategies for sulphur dioxide, and analysis of the role of emissions from Central and Eastern Europe. Idöjárás 96 No. 4. 207-21 (1992).

4 J. Alcamo, R. Shaw and L. Hordijk (eds.), The RAINS Model of Acidification, Science and Strategies in Europe. Kluwer Academic Publishers, Dordrecht (1990).

5 C.A. Gough, P.D. Bailey, B. Biewald, J.C.I. Kuylenstierna and M.J. Chadwick, Environmentally Targeted Objectives for Reducing Acidification in Europe. Energy Policy (in press) (1994).

6 T. Iversen, J. Saltbones, H. Sandnes, A. Eliassen and Ø. Hov, Airborne Transport of Sulphur and Nitrogen over Europe - Model Descriptions and Calculations. EMEP/MSC-W Report 2/89. Oslo (1989).

7 T. Iversen, N.E. Halvorsen, S. Mylona and H. Sandnes, Calculated Budgets for Airborne Acidifying Components in Europe, 1985, 1987, 1989 and 1990. EMEP/MSC-W. Technical Report No. 91, Oslo (1991).

8 M.J. Chadwick and J.C.I. Kuylenstierna, The Relative Sensitivity of Ecosystems in Europe to Acidic Depositions. The Stockholm Environment Institute, Stockholm (1990).

9 G.R. Walsh, An Introduction to Linear Programming. Holt, Rinehart and Winston Ltd. London (1971).

10 H.P. Williams, Model Building in Mathematical Programming. Wiley Interscience, Chichester, UK. 20-30 (1985).

11 L. Schrage, User's Manual for Linear, Integer and Quadratic Programming with LINDO. The Scientific Press, Redwood City, California (1989).

12 P. Nijkamp, Environmental Policy Analysis, Operational Methods and Models. John Wiley and Sons, New York (1980).

13 J.H. Ellis, Acid Rain Control Strategies, Options exist despite uncertainties. Environmental Science and Technology. Vol. 22, No. 11. P 1248 (1988).

14 GEMS, Forest Damage and Air Pollution. Reports of the 1987-1990 forest damage surveys in Europe. Convention on Long-range Transboundary Air Pollution - International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. UNEP/ECE, Geneva (1988 - 1991).

15 J.C.I. Kuylenstierna, Assessment of Ecosystem Sensitivity to Acidic Deposition: Critical Load Estimates, Detriment and Damage. PhD Thesis (Unpublished) (1993).

16 B.O. Rosseland and A. Henriksen, Acidification in Norway - loss of fish populations and the 1000-lake survey 1986. The Science of the Total Environment 96 , 45-56 (1990).