FACULTY OF ECONOMICS AND
APPLIED ECONOMIC SCIENCES
CENTER FOR ECONOMIC STUDIES
ENERGY, TRANSPORT & ENVIRONMENT

1425

KATHOLIEKE
UNIVERSITEIT
LEUVEN

WORKING PAPER SERIES
n°2004-05

The Environmental Costing Model: a tool for more efficient environmental policymaking in Flanders

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July 2004

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a tool for more efficient environmental policymaking in Flanders

This version: March 5, 2004

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Abstract

The environmental costing model (Milieu-Kosten-Model or MKM in Dutch) is a tool for assessing cost-efficiency of environmental policy. The present paper describes the modelling methodology and illustrates it by presenting numerical simulations for selected multi-sector and multi-pollutant emission control problems for Flanders. First, the paper situates the concept of cost-efficiency in the context of Flemish environmental policy and motivates the chosen approach. Secondly, the structure of the numerical simulation model is laid out. The basic model input is an extensive database of potential emission reduction measures for several pollutants and several sectors. Each measure is characterized by its specific emission reduction potential and average abatement cost. The MKM determines, by means of linear programming techniques, least-cost combinations of abatement measures as to satisfy, possibly multi-pollutant, emission standards. Emission reduction targets can be imposed for Flanders as a whole, per sector or even per installation. The measures can be constrained to satisfy "equal treatment" of sectors and several other political feasibility constraints. Thirdly, the features of the model are illustrated by means of a multi-sector (non-ferrous, chemical and ceramics industry) and multi-pollutant (SO_2, NO_x) example. Results show clearly that important cost savings are possible by allowing for more flexibility (emission standards for Flanders as a whole instead of per sector). Cost savings from taking into account explicitly the multi-pollutant nature of environmental regulation are modest for the current test version of the database.

Keywords*:* environmental economics, cost efficiency, multi-pollutant emission control problem, numerical simulation model, linear programming

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1. Context and approach

As a highly populated and strongly industrialised region in the heart of Europe, Flanders is confronted with severe environmental problems in soil, air and water. Since many years the environmental policy of the Flemish (regional) government is aimed at curbing these problems. As a result the environmental quality increases slowly, but costs to the public and private sector are increasing strongly. The share of environmental expenditure in the budget of the Flemish government has increased from 3.5% in 1991 to 5.3% in 2003. In 2003 the Flemish government has spend about €800 million on environmental policy. Local authorities in Flanders are estimated to spend another €700 million, on top of the regional expenditure. Belgian national data show that environmental expenditure by the private sector is even more important and has also grown strongly over the past decade. Total national expenditure of public and private sector together amounted to 1.74% of the Belgian GDP[1] in 2000.

In the evolution towards a better environment, the available environmental measures become more and more expensive. Both during budget negotiations at government level as well as during negotiations with the private sectors which have to comply with environmental policy, the Ministry of Environment is confronted with stringent financial constraints. Consequently, it is essential to obtain an overview of available abatement measures, their costs and emission reduction potential, and to find cost efficient or least-cost solutions to reach the environmental objectives.

Cost-efficiency analysis can also be an important tool for policy-makers in Flanders in the context of international or European environmental policy. The environmental targets for Flanders are to a large extent defined at an international, often European, level. The determination of these international environmental objectives and the burden sharing between countries are increasingly based on economic analyses: for instance the RAINS model (see Alcamo et al 1990 or Hordijk 1991) for the Göteborg Protocol or NEC directive 2001/81/EG and the use of the triptych approach for determining the EU burden sharing for the greenhouse gas emission reduction targets under the 1997 Kyoto Protocol (see Phylipsen et al. 1998). In order to negotiate with a good understanding of the techno-economic consequences on issues as international burden sharing, the regional Flemish policy maker needs information on the cost effectiveness of the possible abatement measures of its private sectors. Sometimes, a cost-efficiency analysis is a compulsory step in order to comply with European directives, e.g. in the Water Framework Directive a cost-efficiency analysis is imposed as part of an overall economic analysis for each river basin.

Cost-efficiency analysis is often a straightforward exercise if only a single pollutant, a single environmental objective and few emission sources have to be taken into account. However, actual policy practice is often more complex involving many pollutants and environmental objectives, many emission sources, many constraints, interactions and trade-offs. In such a setting, a simple overview of (marginal) costs and emission reduction potential of abatement measures is not sufficient. A consistent framework and a tool for simulation and optimisation are needed to advise the policy makers correctly on issues of cost-efficiency. As a consequence, the Flemish Government initiated the construction of a so-called environmental costing model (in Dutch Milieu Kosten Model, abbreviated MKM)[2].

Firstly a background document[3] was written in which the choices concerning the definition of costs and cost-effectiveness and the methodology to analyse the cost-effectiveness of emission reduction measures and policy instruments are explained. Subsequently, the construction of a coherent database structure was initiated. This database is currently being filled with information concerning emission sources (e.g. production activity level, emission factor) and emission reduction measures (e.g. average abatement costs, emission reduction potential, application and applicability rates). Simultaneously, an optimization framework was developed as a tool to allocate emission reduction efforts between different emission sources in a cost-effective way, taking into account the "all-or-nothing" nature of many measures (application rates are typically integer instead of continuous decision variables) and multiple pollutant effects[4].

Initially, the MKM model is developed for a test case, namely the most important industrial sources of SO_2, NO_x en VOC in Flanders. The choice of this test case was inspired by the emission targets that Directive 2001/81/EC (national emission ceilings for certain atmospheric pollutants) imposes on Belgium (and Flanders). Consequently,

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[1] see Federaal Planbureau (2003).

[2] Since June 2001, the BAT Centre of the Flemish Institute for Environmental Research is charged with the construction of the MKM. The project is financed by the Flemish Government and supported by a committee of representatives of the Flemish Government and independent experts. With regard to the actual programming of the MKM, the BAT Centre cooperates closely with Dr. J. Eyckmans.

[3] See Meynaerts et al. (2003).

[4] Planned next steps in the development of the MKM are the integration of cost-effectiveness analysis of policy instruments (such as taxes and tradable permits) and the linking of the MKM to other models e.g. ecological models, macro-economic models.

the present paper focuses on the pilot version of the MKM. In the near future, the MKM will be extended to and/or adapted for other emission sources (e.g. households, agriculture, transport), and other pollutants (e.g. particulate matter in air and BOD, COD and phosphorus in water).

This paper is organized as follows. Section 2 describes the theoretical background of the MKM model, the modelling assumptions and the different possible choices of optimization scenarios. Section 3 reports on a simulation exercise illustrating the main features and advantages of the MKM model. Section 4 concludes and gives suggestions for further research.

2. Model description

2.1 General: features of the model

The core of the MKM is a database of emission reduction measures with their associated emission reduction potential and unit (or average) cost. Due to the large number of individual emission sources within the Flemish industry, it is impossible to consider and assess each and every installation individually. Therefore, installations are assigned to representative categories of installations, so-called "*reference installations*", according to following criteria:

- for all installations, which can be assigned to a certain reference installation, the same emission abatement techniques can be applied,
- all installations, which are assigned to a reference installation, show similar abatement results for given emission abatement options. The cost parameters of a certain abatement measure are considered the same for all installations that are assigned to a specific reference installation.

All emission abatement measures in the MKM database are defined as *exclusive*, i.e. at most one emission reduction measure or technique can be operational at the same time on a particular reference installation. However, the database is constructed such that each of these measures can possibly consist of a combination of several technical emission reduction measures.

By means of *linear programming*[5], the MKM selects from the database those abatement measures that can achieve a set of predetermined emission targets in a cost-

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[5] Programming is performed in GAMS (General Algebraic Modelling System). For more information: http://www.gams.com.

effective way i.e. at the lowest possible cost. The set up and modelling approach of the MKM is inspired by, among others, Brink (2003).

The model is *one-shot dynamic*, i.e. it considers only one future time period (e.g. the year 2010) in which abatement measures can be implemented and emission ceilings can be imposed.

Emissions of pollutants are *activity based*, i.e. they depend on the activity level of the emission sources. As a result the MKM could be linked to input-output, partial or general equilibrium models for the relevant sectors of the Flemish economy. However, the model that is described in this paper is not linked with such models yet.

The MKM operates in a *multi-source* and *multi-pollutant* context. The formulation of the model allows for positive or negative interaction effects between pollutants (for instance, reducing SO_2-emissions, by means of scrubbers and filters, might generate more solid waste or require higher energy input and give rise to associated emissions). The formulation also allows for emission ceilings or emission reduction targets to be set at the overall Flemish level, at sector level or at (reference) installation level.

Application rates of abatement measures are continuous decision variables corresponding to the interpretation that not necessarily all installations are to be equipped with the same abatement measure. For instance, the Flemish Government might choose to impose the implementation of abatement measure A on one-third of the installations and measure B on the rest[6]. However, if this interpretation of the application rates cannot be justified due to political or legal reasons, also an "all-or-nothing" assumption or binary application rate can be assumed.

2.2 Description of the endogenous and exogenous variables[7]

2.2.1 Emissions

Emissions of a reference installation depend (for a particular pollutant) on the activity level of this installation (parameter y), the emission factor (parameter ef) and the abatement measures that are installed.

Abatement measures can be applied in whatever degree and the extent of application is measured by the so-called application rate (variable A). The application rate is the most important decision variable of the MKM: $A \in [0,1]$ or the application rate is

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[6] Due to the exclusivity assumption, the sum of all application rates for a given reference installation cannot exceed 100%.

[7] Endogenous variables are in capitals, exogenous parameters are in lower-case letters. All symbols are listed in the Appendix.

limited by its upper bound, the maximum technical possible application of a certain measure to a certain reference installation, (parameter *aup*) $A \in [0, aup]$. The full emission reduction effect of a particular abatement measure M is the product of its application rate times its efficiency (parameter *effic*) to reduce a particular pollutant:

Equation [1]: definition total emissions per reference installation RI and pollutant P

$$E(RI,P) = ef(RI,P) \cdot y(RI) \cdot \left[1 - \sum_{M} A(RI,M) \cdot effic(RI,M,P)\right]$$

Total emissions for a particular pollutant P are defined as the sum of its emissions over all reference installations RI:

Equation [2]: definition total emissions per pollutant P

$$E(P) = \sum_{RI} E(RI,P) \quad \forall P$$

No-policy emissions are defined as the product of the activity level (for instance tons of steal output) times an emission factor. Hence, the concept of no-policy emissions assumes that no abatement measures are operational (i.e. all $A(RI,M) = 0$).

Parameter no-policy emissions per reference installation RI and pollutant P

$$e^{0}(RI,P) = ef(RI,P) \cdot y(RI)$$

Business-as-usual (BAU) emissions differ from no policy emissions because they take into account planned abatement measures. These planned abatement measures are taken into account by imposing that application rates are equal to their lower bound (parameter *alow*).

Parameter Business-as-Usual emissions per reference installation RI and pollutant P

$$e^{BAU}\left(RI,P\right)=E^{0}\left(RI,P\right)\cdot\left[1-\sum_{M}alow\left(RI,M\right)\cdot effic\left(RI,M,P\right)\right]$$

Of course, if no abatement measures are planned (i.e. if all $alow\left(RI,M\right)=0$), no-policy and BAU emissions coincide.

2.2.2 First-best versus second-best simulations

The distinction between no-policy and BAU emissions is taken into account in the MKM. The model can run a cost minimisation problem for two scenarios:

(1) *first-best*: no prior lower bounds are imposed on the application rates,
(2) *second-best:* the lower bounds apply.

In the first-best scenario it is assumed that planned measures can still be annihilated whereas in the second-best scenario planned measures will be installed. Clearly, the first-best scenario will be cheaper than second-best since it allows for more flexibility in the combination of measures.

2.2.3. Exclusivity of abatement measures

Abatement measures are defined as exclusive meaning that on a particular emission source, two or more abatement measures cannot be implemented at the same time. Of course, an emission reduction measure can consist of a combination of techniques (like a best-practice measure plus pre-processing of the fuel plus a smoke stack scrubber). In the MKM, this exclusivity is imposed by the restriction that for any given reference installation, the application rates of all implemented abatement measures M should not exceed 100%:

Equation [3]: exclusiveness of abatement measures M per reference installation RI for continuous application rates

$$\sum_{M}A\left(RI,M\right)\leq 1\quad\forall RI$$

Note that this restriction does not exclude the possibility that a given reference installation is equipped with two (or more) measures. The restriction only imposes that the sum of all application rates should not exceed 100% or the maximum upper bound. The MKM allows that different emission sources, using the same type of (reference) installation, implement different abatement measures. However, no emission source has more than one measure operational at the same time.

2.2.4 Binary application rates or "all-or-nothing"

For some purposes, the latter property of the MKM is inconvenient: it can be argued that it violates the legal equality impediment or it might be politically infeasible to treat the emission sources that are assigned to the same reference installation differently. If all the emission sources that are assigned to the same reference installation, have to implement the same technique, the application rates should be binary instead of continuous. Consequently, the binary decision variable *BIN(RI,M)* is introduced and the following restriction is imposed on the application rates:

Equation [4]: binary application rate per reference installation RI and abatement measure M

$$A(RI,M) = alow(RI,M) + BIN(RI,M) \cdot \left[aup(RI,M) - alow(RI,M) \right] \quad \forall RI \in CONRI(RI)$$

as *BIN(RI,M)* are binary variables, they can only be 0 or 1. If *BIN(RI,M)*=0, the application rate is at its lower bound. In the other case when *BIN(RI,M)*=1, the application rate is at its upper bound. In order to guarantee exclusivity of abatement measures in case of binary application rates, an additional restriction has to be imposed:

Equation [5]: exclusiveness of measures per reference installation RI and abatement measures M for binary application rates

$$\sum_{M} BIN(RI,M) \leq 1 \quad \forall RI \in BINRI(RI)$$

This “all-or-nothing” version of the MKM comes however at a price, the optimisation problem now contains binary variables and requires more complex and time consuming optimisation algorithms (i.e. mixed integer programming). The formulation of continuous and binary application rates can be mixed such that some reference installations are subject to the “all-or-nothing” assumption $(RI \in BINRI)$ whereas others are not $(RI \in CONRI)$.

2.2.5. Emission ceilings

Emission ceilings can be imposed at different levels. The most detailed level is the level of a reference installation. MKM allows for different emission ceilings or reduction targets to be imposed on different reference installations. Alternatively, emission ceilings can be specified at the level of a sector (a sector is a set of reference installations) or at the top level (i.e. Flemish industry). It is also possible to use a mix of ceilings at different levels.

Equation [6]: Flemish emission standard en per pollutant P

$$E\left(P\right) \leq en\left(P\right) \quad \forall P$$

Equation [7]: emission standard en^{RI} per reference installation RI and pollutant P

$$E\left(RI,P\right) \leq en^{RI}\left(RI,P\right) \quad \forall RI;\forall P$$

Equation [8]: emission standard en^{S} per sector S and pollutant P

$$\sum_{RI \in S} E\left(RI,P\right) \leq en^{S}\left(S,P\right) \quad \forall S;\forall P$$

with the sector S defined as a group of reference installations RI.

For each of the ceilings, the default value is assumed to be equal to the no-policy or BAU emissions. This means that we start from a situation without a (binding) emission ceiling. The user has to specify emission ceilings that are strictly smaller than no-policy or BAU emission levels in order to activate the particular emission ceilings??? in the optimisation model.

2.2.6 Cost of abatement measures

Total emission abatement costs for a particular reference installation are given by the costs of all measures that are implemented. The variable cost of abatement measures is defined as the product of the application rate, the specific cost (parameter *sc,* expressed as the cost per unit of activity) and the activity level of the reference installation. A fixed cost component (parameter *fc*, expressed as the total fixed cost for all the reference installations of this particular type) can also be included though only for the reference installations subject to the binary application rates.

Equation [9]: total annual cost per reference installation RI (continuous application rates)

$$TC(RI) = \sum_{M} \left[sc(RI,M) \cdot y(RI) \cdot A(RI,M) \right] \quad \forall RI \in CONRI(RI)$$

Equation [10]: total annual cost per reference installation RI (binary application rates)

$$TC(RI) = \sum_{M} \left[sc(RI,M) \cdot y(RI) \cdot A(RI,M) + fc(RI,M) \cdot BIN(RI,M) \right]$$
$$\forall RI \in BINRI(RI)$$

Finally, the costs are aggregated to obtain the total cost for Flanders for a given set of emission ceilings and cost minimising abatement measures:

Equation [11]: total annual cost for Flanders

$$OBJ = TC = \sum_{RI} TC(RI)$$

The latter equation is defined as the objective variable to be minimised in the linear programming problem consisting of equations [1] to [11]. This set of equations defines the standard version of the MKM.

2.2.7 Maximum reduction potential

Finally, the MKM can also estimate the maximum reduction potential for a particular pollutant P. For this purpose, the model minimises an alternative objective function without considering the emission ceilings nor the abatement costs. The maximum reduction potential has to be interpreted carefully since it is only valid for a particular version of the model (particular combination of continuous and binary application rates reference installations, particular structure of emission ceilings, e.g. Flemish or sector ceilings) and does not take into account possible interaction effects when different ceilings are imposed on different pollutants at the same time.

Equation [12]: Maximum reduction potential for particular pollutant P

$$OBJ = E\left(P\right)$$

The latter equation is defined as the objective variable to be minimised in the linear programming problem consisting of equations [1] to [5], [9], [10] and [12]. This is the maximum reduction potential version of the MKM.

3. Numerical Illustration

The sectors covered in the numerical simulation exercise are the non-ferrous metals sector, the anorganic chemical sector, the organic chemical sector and the ceramics industry. Each of these sectors is split into a certain number of reference installations. E.g. in the ceramics industry 5 reference installation types are distinguished according to the sulphur content of the clay used as input in the production process. In total, 30 types of reference installations are included in the current database and 31 emission abatement measures. More details on the emission control measures, their emission reduction efficiency, minimal and maximal application rate and unit costs can be found in Table 6 in Appendix 2. Business-As-Usual emissions for all reference installations are reported in Table 5 in Appendix 2.

In order to illustrate the MKM we present results of six different simulations that differ in two dimensions. First we investigate the impact of allowing for more flexibility in order to achieve the overall Flemish emission reduction targets. We compare scenarios with *sectoral emission ceilings* and scenarios with *Flemish emission ceilings*. In the sectoral emission ceilings scenarios, every sector has to meet the emission ceiling for the different pollutants. In the Flemish emission ceilings scenarios it is sufficient that the overall target is achieved, individual sectors can emit more or less than the overall reduction target. We expect important cost savings from allowing for a more flexible system of environmental regulation and use the MKM to quantify these savings.

The second dimension concerns the multi-pollutant aspect. For each of the scenarios described earlier, we consider three variants. On the one hand, the first two variants relate to the separate optimization for a single pollutant only, SO2 and NOx respectively. Only for a single pollutant, an emissions ceiling is imposed without concern for potential joint emission reductions in the other pollutant. The third variant on the other hand, concerns the joint cost minimization when emission reduction standards are imposed for both pollutants simultaneously. Again we expect important cost savings from the joint cost minimization approach and we use the MKM to estimate these cost savings.

All simulations refer to the same Flemish emission reduction targets of 50% for SO2 and 25% for NOx emissions. The target year is 2010 and the reduction percentages are expressed relative to the business-as-usual (BAU) emission levels. The later BAU emission levels refer to the situation in 2010 without additional environmental policies than the ones that are currently planned. Notice that for some sectors and installations, the BAU scenario for 2010 does already include some emission abatement measures as a result of current environmental regulations. These ceilings are purely illustrative but were chosen in line with the Flemish international obligations under the Göteborg Protocol[8].

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[8] The Göteborg Protocol imposes emission ceilings on Belgium that have been distributed over the three Belgian regions. According to this national burden sharing, Flanders should reduce its NO_x emissions by 38.6% and SO_2 emissions by 71.3% compared to 1990 emission levels. Since the MKM database does not cover all Flemish emissions of these gases, a realistic implementation of the Göteborg Protocol cannot be simulated.

INSERT TABLE 1 ABOUT HERE

Table 1 refers to the *Flemish emission ceilings scenarios* and reports the details for each reference type of installation and for each sector of the abatement measures chosen and the reduction of both pollutants expressed as a percentage of BAU emissions. Only those reference installations for which an abatement measure has been chosen are reported. In the cost efficient solution reported in Table 1, only reference installations that have to implement additional abatement measures on top of the BAU situation are mentioned.

First notice that for all scenarios, the final amount of emission abatement is a little higher than the actual emission norm, indicating that there is some overachievement of the environmental regulation. The reason for that is the binary nature of the solution. We have imposed that abatement measures are to be applied to all the reference installations of a particular type (the so-called "all-or-nothing" assumption explained in section 2).

Secondly, the spill over effects of the separate cost minimizations to the other pollutant than the one that is constrained, are very small. They amount to less than one percent in both cases.

Thirdly, concerning the multi-pollutant aspect of the environmental regulation, we have marked in bold in the third part of Table 1 (*SO_2-NO_x jointly*) all reference installations for which the joint cost minimization picks different measures than in the separate cost minimizations. This to highlight that the joint cost minimizing solution is not just the sum of the separate optimization exercises. In particular we notice that Reference Installation 1 is involved in the joint solution but is not using any reduction measure in either of the separate optimizations. Reference installations 3 and 18 are not required to apply reduction measures in the joint optimization[9] although they were activating measures in some of the separate optimizations. Finally, notice that for Reference Installation 8, a different abatement measure is chosen in the *SO_2-NO_x jointly* scenario (measure 9) compared to the *SO_2 separately* scenario (measure 11).

INSERT TABLE 2 ABOUT HERE

Although we observe from Table 1 a substantial difference in the cost minimizing solution for both pollutants taken together compared to the separate optimizations, the

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[9] This case is indicated as a "**0**" in the column "*measure*".

cost savings are relatively modest. The sum of the abatement costs for scenarios *SO_2 separately* and *NO_x separately* amount to €15216.29 (x1000). This is €433,71 (x1000) more than in the *SO_2-NO_x jointly* scenario or 2.85% compared with most expensive solution. These relatively small cost savings are probably due to the fact that the current database of abatement measures consists primarily of measures that can only reduce one pollutant at a time. It is expected that more multi-pollutant measures will enter the database in the near future as data for additional sectors and pollutants will be added.

INSERT TABLE 3 ABOUT HERE

We now turn to the family of *sectoral emission ceilings* scenarios. Table 3 is the counterpart of Table 1 for the sectoral emission ceilings. First, notice that more Reference Installations are involved in these solutions than in the solution with an overall Flemish emission ceiling. This is due to the more stringent requirement that every sector has to meet the emission targets instead of focusing only on total emissions for Flanders as in Table 1. Secondly, we observe in the *SO_2-NO_x jointly* section of Table 3 that the joint optimization is also rather different in terms of Reference Installations involved compared to the separate optimization exercises. Reference Installation 1 is invoked in the joint scenario and was not active in either of the separate scenarios. Reference Installation 6 is not called upon anymore in the joint cost minimization and Reference Installation 7 chooses for a less powerful emission reduction technology (measure 9 instead of 11) in terms of SO_2.

INSERT TABLE 4 ABOUT HERE

Concerning the abatement costs, we observe that the cost savings from the joint optimization are small, only 1.26%, in the *sectoral emission ceilings* scenario.

Given the cost data in Table 2 and Table 3, we are now able to calculate the cost savings from allowing for more flexibility in environmental regulation. Allowing for overall Flemish emission ceilings for both pollutants instead of specifying reduction targets for all sectors individually generates important cost savings. Total costs for the *SO_2-NO_x jointly* scenario amount to €28682.90 (x1000) under the *sectoral emission ceilings* against only €14782.58 (x1000) under the *Flemish emission ceilings*. Hence cost savings amount to as much as €13900.32 (x1000) or 48.46% compared to the most expensive scenario.

4. Conclusions and suggestions for further research

As a general conclusion from the simulation exercises, we can conclude that in order to promote cost efficiency in Flemish environmental regulation concerning air pollutants SO_2 and NO_x, it is most important to allow for as much flexibility as possible in terms of the distribution of abatement efforts. The scenario under which all sectors would be confronted with an identical emission reduction target is twice as costly as a scenario in which focuses only on the Flemish target as a whole and does not specify sectoral environmental objectives. This has important implications for the choice of environmental policy instruments to implement the cost efficient solutions. Our results show that there are important cost savings from using a cost efficient environmental policy instrument like emission taxes or tradable permits instead of a more traditional approach based on identical sectoral emission standards.

In spite of the flexibility of the MKM, the model has certain limitations that can be subject of further research. One of the most important limitations of the current version of the model is that it is static. Consequently, the lifetime of abatement measures and the remaining (economic) lifetime of existing production and abatement installations are not taken into account. Since there is only one future time period, many interesting questions cannot be answered properly. A first and challenging extension is a fully dynamic version of the model.

Secondly, the current version of the model can take fixed costs into account only for binary application rates. Extension of this option to the continuous application rates is needed.

Thirdly, allowing for non-exclusive measures (hence for combinations of abatement measures) would alleviate the burden of the database construction. This extension would remove the necessity to model each possible combination of technical abatement measures as a separate measure in the model.

Fourthly, one of the advantages of the current version of the model is that it is written in function of the (emission related) activity levels of the emission sources. As a consequence, the coupling of the MKM to an economic model of the Flemish economy would be most interesting. The approach by Dellink et al (2003) might serve here as an example.

Finally, currently the MKM does only model emission ceilings. It would be interesting to evaluate the cost-effectiveness of other environmental policy instruments, in particular emission charges or tradable permits in addition to or within the MKM framework.

References

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

Brink, C. (2003), *Modelling cost-effectiveness of interrelated emission reduction strategies - the case of agriculture in Europe*, Ph.D. thesis (Wageningen University), available at http://www.sls.wageningen-ur.nl/enr/staff/brink/.

Dellink, R.B., Hofkes, M.W., van Ierland, E.C. and Verbruggen, H. (2002), *Dynamic modelling of pollution abatement in a CGE framework*, mimeo (Wageningen University), available at http://www.sls.wageningen-ur.nl/enr/staff/dellink/.

Federaal Planbureau (2003), *De Belgische milieurekeningen*, planning paper 93, available at http://www.plan.be.

Hordijk, L. (1991) Use of the RAINS Models in Acid Rain Negotiations in Europe, *Environmental Science and Technology* **25**, 596-603.

Meynaerts, E., Ochelen, S. and Vercaemst, P. (2003), *Milieukostenmodel voor Vlaanderen – Achtergronddocument* (VITO, Mol), available at http://www.emis.be.

Phylipsen, G.J.M., Bode, J.W., Blok, K., Merkus, H. and Metz, B. (1998), A triptych sectoral approach to burden sharing; Greenhouse gas emissions in the European Bubble, *Energy Policy* **26**, 929-943.

Van Regemorter, D. and Goldstein, G. (1998), Development Of MARKAL – Towards a Partial Equilibrium Model. ETSAP Technical Paper http://www.ecn.nl/unit_bs/etsap

Appendix 1: Simulation results

Table 1: details of implemented abatement measures (Flemish emission ceilings)

	SO_2 separately			NO_x separately			SO_2-NO_x jointly		
	Measure	Reduction SO_2 (%)	Reduction NO_x (%)	Measure	Reduction SO_2 (%)	Reduction NO_x (%)	Measure	Reduction SO_2 (%)	Reduction NO_x (%)
RI=1							**4**	**99.78**	**70.01**
RI=3	3	98.53	22.06	3	98.53	22.06	**0**		
RI=6	7	90.00					7	90.00	
RI=7	7	88.66					7	88.66	
RI=8	11	93.46					**9**	**86.92**	
RI=10	9	79.64					9	79.64	
RI=11	17	54.96					17	54.96	
RI=14				19		24.78	19		24.78
RI=17				18		77.00	18		77.00
RI=18				19		10.00	**0**		
RI=29	30	90.00					30	90.00	
RI=30	30	90.00					30	90.00	
S=1		77.62	2.27		2.38	2.27		76.82	7.63
S=2		44.80	0.00		0.00	1.15		44.80	1.15
S=3		0.00	0.00		0.00	33.63		0.00	33.32
S=4		49.45	0.00		0.00	0.00		49.45	0.00
Flanders		50.13	0.17		0.93	25.02		50.01	25.19
norm		*50.00*	*0.00*		*0.00*	*25.00*		*50.00*	*25.00*

Table 2: Cost details (Flemish emission ceilings)

	SO_2 separately		No_x separately		SO_2-No_x jointly	
	Optimal (1000 €)	Optimal (%)	Optimal (1000 €)	Optimal (%)	Optimal (1000 €)	Optimal (%)
RI=1					273.58	1.85
RI=3	58.76	0.46	58.76	2.50		
RI=6	732.86	5.70			732.86	4.96
RI=7	1099.35	8.54			1099.35	7.44
RI=8	1205.06	9.37			722.28	4.89
RI=10	1286.22	10.00			1286.22	8.70
RI=11	1242.43	9.66			1242.43	8.41
RI=14			21.12	0.90	21.12	0.14
RI=17			2163.15	92.05	2163.15	14.63
RI=18			106.98	4.55		
RI=29	1220.33	9.49			1220.33	8.26
RI=30	6021.27	46.80			6021.27	40.73
S=1	4382.25	34.06	58.76	2.50	4114.28	27.83
S=2	1242.43	9.66	21.12	0.90	1263.55	8.55
S=3	0.00	0.00	2270.13	96.60	2163.15	14.63
S=4	7241.61	56.28	0.00	0.00	7241.61	48.99
Flanders	12866.28	100.00	2350.01	100.00	14782.58	100.00

Total cost for scenarios SO_2 separately and No_x separately: 15216.29.

Cost savings of joint optimization: €433710 or 2.85% compared with most expensive solution.

Table 3: details of implemented abatement measures (sectoral emission ceilings)

	SO_2 separately			NO_x separately			SO_2-NO_x jointly		
	Measure	Reduction SO_2 (%)	Reduction NO_x (%)	Measure	Reduction SO_2 (%)	Reduction NO_x (%)	Measure	Reduction SO_2 (%)	Reduction NO_x (%)
RI=1	4	99.78	70.01	4	99.78	70.01	4	99.78	70.01
RI=2				5	84.40	80.00	5	84.40	80.00
RI=3				4	98.53	53.33	4	98.53	53.33
RI=4				1		6.79	1		6.79
RI=6	7	90.00					**0**		
RI=7	6	49.26					**7**	**88.66**	
RI=8	9	86.92					9	86.92	
RI=11	15	62.81					15	62.81	
RI=12				18		47.31	18		47.31
RI=16	17	61.83					17	61.83	
RI=17				18		77.00	18		77.00
RI=19	23	99.68	12.00				23	99.68	12.00
RI=22	17	36.45					17	36.45	
RI=27	27	20.00					27	20.00	
RI=29	30	90.00					30	90.00	
RI=30	30	90.00					30	90.00	
S=1		50.17	7.63		6.01	25.97		50.66	25.97
Norm		*50.00*				*25.00*		*50.00*	*25.00*
S=2		51.20	0.00		0.00	35.64		51.20	35.64
Norm		*50.00*				*25.00*		*50.00*	*25.00*
S=3		53.10	0.41		0.00	33.32		53.10	33.74
Norm		*50.00*				*25.00*		*50.00*	*25.00*
S=4		51.25	0.00		0.00	0.00		51.25	0.00
Norm		*50.00*						*50.00*	
Flanders		51.17	0.87		0.94	33.22		51.24	33.52

Table 4: Cost details sectoral emission ceilings

	SO_2 separately		No_x separately		SO_2-No_x jointly	
	Optimal (1000 €)	Optimal (%)	Optimal (1000 €)	Optimal (%)	Optimal (1000 €)	Optimal (%)
RI=1	273.58	1.73	273.58	2.07	273.58	0.95
RI=2			982.41	7.42	982.41	3.43
RI=3			284.44	2.15	284.44	0.99
RI=4			488.13	3.69	488.13	1.70
RI=6	732.86	4.64				
RI=7	459.382	2.91			1099.35	3.83
RI=8	722.28	4.57			722.28	2.52
RI=11	2411.90	15.26			2411.90	8.41
RI=12			9048.38	68.34	9048.38	31.55
RI=16	1187.04	7.51			1187.04	4.14
RI=17			2163.15	16.34	2163.15	7.54
RI=19	1035.73	6.55			1035.73	3.61
RI=22	930.66	5.89			930.66	3.25
RI=27	814.27	5.15			814.27	2.84
RI=29	1220.33	7.72			1220.33	4.26
RI=30	6021.27	38.09			6021.27	20.99
S=1	2188.10	13.84	2028.56	15.32	3850.18	13.42
S=2	2411.90	15.26	9048.38	68.34	11460.28	39.96
S=3	3153.42	19.95	2163.15	16.34	5316.57	18.54
S=4	8055.88	50.96	0.00	0.00	8055.88	28.09
Flanders	15809.29	100.00	13240.08	100.00	28682.90	100.00

Total cost for scenarios SO_2 separately and No_x separately: 29049.37.

Cost savings of joint optimization: €366470 or 1.26% compared with most expensive solution.

Appendix 2: MKM database

Table 5: BAU emission levels (ton)

	SO_2	NO_x
RI=1	146.04	72.73
RI=2	3.90	81.60
RI=3	98.94	68.78
RI=4	8.18	300.99
RI=5	43.56	56.74
RI=6	463.18	72.69
RI=7	853.35	8.93
RI=8	1235.80	0.00
RI=9	297.24	0.00
RI=10	950.10	5.03
RI=11	4988.80	49.60
RI=12	1100.10	1308.51
RI=13	29.79	74.61
RI=14	0.89	80.72
RI=15	0.00	223.59
RI=16	879.50	133.80
RI=17	4.60	2844.41
RI=18	2.76	204.00
RI=19	138.64	226.67
RI=20	0.82	503.80
RI=21	2.23	468.00
RI=22	167.91	606.39
RI=23	0.87	518.00
RI=24	1.74	700.00
RI=25	200.51	367.37
RI=26	801.00	0.00
RI=27	1306.00	0.00
RI=28	4438.00	0.00
RI=29	1255.00	0.00
RI=30	6726.00	0.00
S=1	4100.29	667.50
S=2	6119.58	1737.04
S=3	1399.57	6572.44
S=4	14526.00	0.00
FlanderS	26145.44	8976.98

Table 6: Emission abatement measures

		$effic(RI,M,SO_2)$	$effic(RI,M,NO_x)$	*alow(RI,M)*	*aup(RI,M)*	*sc(RI,M)*
RI=1	M=4	0.998	0.700	0.000	99.98	734.18
RI=2	M=3	0.844	0.000	0.000	100.00	1.31
	M=5	0.844	0.800	0.000	100.00	604.23
RI=3	M=3	0.994	0.223	0.000	99.09	73.01
	M=4	0.994	0.538	0.000	99.09	353.40
RI=4	M=1	0.000	0.800	0.000	8.49	1981.26
	M=2	0.000	0.425	0.000	8.49	142.20
RI=5						
RI=6	M=7	0.900	0.000	0.000	100.00	244.29
RI=7	M=6	0.500	0.000	0.000	98.52	116.58
	M=7	0.900	0.000	0.000	98.52	278.98
RI=8	M=8	0.824	0.000	0.000	100.00	1013.64
	M=9	0.869	0.000	0.000	100.00	722.28
	M=10	0.902	0.000	0.000	100.00	1592.67
	M=11	0.935	0.000	0.000	100.00	1205.06
	M=12	0.935	0.000	0.000	100.00	1573.61
	M=13	0.902	0.000	0.000	100.00	1588.36
	M=14	0.935	0.000	0.000	100.00	1778.92
RI=9	M=8	0.786	0.000	0.000	100.00	1015.88
	M=9	0.726	0.000	0.000	100.00	572.57
	M=10	0.590	0.000	0.000	100.00	652.10
	M=11	0.726	0.000	0.000	100.00	788.84
RI=10	M=9	0.796	0.000	0.000	100.00	643.11
	M=10	0.696	0.000	0.000	100.00	846.11
	M=11	0.796	0.000	0.000	100.00	921.69
RI=11	M=15	0.800	0.000	0.000	78.51	614.41
	M=16	0.200	0.000	0.000	78.51	115.74
	M=17	0.700	0.000	0.000	78.51	316.50
RI=12	M=18	0.000	0.800	0.000	59.13	588.54
RI=13						
RI=14	M=18	0.000	0.900	0.000	74.33	481.67
	M=19	0.000	0.333	0.000	74.33	11.19
	M=20	0.000	0.933	0.000	74.33	492.86
RI=15	M=26	0.000	0.900	0.000	100.00	523.00
RI=16	M=17	0.700	0.000	0.000	88.33	67.19
RI=17	M=18	0.000	0.800	0.000	96.25	280.93
RI=18	M=19	0.000	0.100	0.000	100.00	83.58
RI=19	M=23	0.997	0.120	0.000	100.00	446.43
RI=20	M=26	0.000	0.500	0.000	82.58	883.02
RI=21	M=18	0.000	0.900	0.000	100.00	415.38
	M=19	0.000	0.150	0.000	37.78	28.70
	M=20	0.000	0.490	0.000	100.00	185.63
RI=22	M=17	0.850	0.000	0.000	100.00	339.12
	M=18	0.000	0.900	0.000	36.44	2119.64
	M=23	0.996	0.145	0.000	42.88	820.01
	M=24	0.996	0.473	0.000	100.00	1592.41
	M=25	0.364	0.328	0.000	100.00	917.81
RI=23	M=26	0.000	0.500	0.000	100.00	600.92
RI=24	M=18	0.000	0.900	0.000	100.00	562.21
	M=19	0.000	0.150	0.000	82.86	33.03
	M=20	0.000	0.896	0.000	100.00	498.88

Table 6: Emission abatement measures (continued)

		$effic(RI,M,SO_2)$	$effic(RI,M,NO_x)$	$alow(RI,M)$	$aup(RI,M)$	$sc(RI,M)$
RI=25	M=18	0.000	0.900	0.000	100.00	361.30
	M=23	0.990	0.294	0.000	39.47	821.57
	M=24	0.990	0.650	0.000	100.00	964.17
	M=20	0.000	0.933	0.000	74.33	492.86
RI=26	M=27	0.200	0.000	0.000	100.00	89.39
	M=28	0.430	0.000	0.000	100.00	189.13
	M=29	0.200	0.000	0.000	100.00	329.38
	M=30	0.900	0.000	0.000	100.00	320.61
	M=31	0.500	0.000	0.000	100.00	287.59
RI=27	M=27	0.200	0.000	0.000	100.00	135.71
	M=28	0.430	0.000	0.000	100.00	289.54
	M=29	0.200	0.000	0.000	100.00	359.45
	M=30	0.900	0.000	0.000	100.00	414.70
	M=31	0.500	0.000	0.000	100.00	358.39
RI=28	M=27	0.200	0.000	0.000	100.00	163.07
	M=28	0.430	0.000	0.000	100.00	345.45
	M=29	0.200	0.000	0.000	100.00	376.48
	M=30	0.900	0.000	0.000	100.00	464.76
	M=31	0.500	0.000	0.000	100.00	399.79
RI=29	M=27	0.200	0.000	0.000	100.00	222.27
	M=28	0.430	0.000	0.000	100.00	488.67
	M=29	0.200	0.000	0.000	100.00	416.97
	M=30	0.900	0.000	0.000	100.00	610.17
	M=31	0.500	0.000	0.000	100.00	503.34
RI=30	M=27	0.200	0.000	0.000	100.00	245.86
	M=28	0.430	0.000	0.000	100.00	545.40
	M=29	0.200	0.000	0.000	100.00	435.93
	M=30	0.900	0.000	0.000	100.00	669.03
	M=31	0.500	0.000	0.000	100.00	543.20

Appendix 3: notation

Sets or indices

RI	Reference Installations
CONRI(RI)	Reference installations subject to continuous application rates
BIN(RI)	Reference installations subject to binary application rates
S	Sectors
M	Measures
P	Pollutants

Endogenous Variables

	Description	Takes values	Units
$A(RI,M)$	Application rate	Between alow(RI,M) and aup(RI,M)	
$BIN(RI,M)$	Binary application rate	Either 0 or 1	
$E(RI,P)$	Emissions per reference installation		Ton
$E(P)$	Total emissions		
$TC(RI)$	Total cost per reference installation		
TC	Total cost Flanders		
OBJ	Objective variable		

Exogenous parameters

$y(RI)$	Production activity level	Ton
$ef(RI,P)$	Emission factor	Ton
$effic(RI,M,P)$	Efficiency measure	Percent
$alow(RI,M)$	Lower bound application rate	Percent
$aup(RI,M)$	Upper bound application rate	Percent
$sc(RI,M)$	Specific cost	Euro
$en(P)$	Flemish emission ceiling	ton
$en^{S}(S,P)$	Sector emission ceiling	Ton
$en^{RI}(RI,P)$	Reference installation emission ceiling	Ton

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