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Discussion Paper Number 30 July 1986

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Advantages and Limitations

I-0 has both advantages and limitations for environmental analysis. It can assist in the analysis of pollution for much the same reasons that it is useful in economic analysis. Its great strength lies in its ability to capture the complex interrelationships between producing sectors through a set of simultaneous equations. The linearity of these equations makes them easily solvable by computer, even for models with several hundred sectors. A wide variety of possible outcomes can be investigated, ranging from straight forecasts to policy options, from impacts on quantities to impacts on costs and prices. However, the assumption of linearity (with constant returns to scale in production and no substitution), which makes inter-industry analysis so tractable, carries the penalty of offering a less than exact representation of a largely non-linear world. In many cases, the larger the changes considered, the more inaccurate are likely to be the forecasts or projections.

The demands that the basic I-0 model makes on data are considerable. These requirements are much increased when the model is extended to account for the generation, emission and abatement of pollutants. These problems can be exacerbated by the fact that it is often desirable to analyse pollution issues at a regional or sub-regional level, for some purposes, or at a continental or global level for others.

This is clearly the case for many of the issues connected with sulphur dioxide and carbon dioxide. However, regional I-O and pollution data are much less frequently available than national data. And although a global, multi-regional model including some pollutants has been constructed (Leontief et al., 1977), it proved a difficult task, requiring much proxy data to substitute for what was unavailable.

There are two further limitations, connected with what happens after pollutants have been emitted from their sources. The first is that many I-O models, although certainly not all, do not try to analyse what becomes of pollutants after discharge and what effects ensue in particular locations as a result of the processes of transportation and transformation in the environment. The second is that even if these effects are traced through, there remains the problem of valuing, in terms of social cost-benefit analysis, both environmental commodities and pollution damage.

Valuation is necessary because the market system either fails to provide a price for these things or provides a price that acts as an inappropriate indicator of value. The valuation matters because it is a vital input in the design of appropriate environmental and pollution control strategies. However, the problem of valuation is not one that is particular to I-O analysis. It is a more general problem in environmental economics, which has received much recent attention. This work has been controversial, partly for technical reasons and partly because it has to do with ethical issues, such as the value of human health and life for both current and future generations (Freeman, 1979; Jones-Lee, 1982; Jones-Lee, et al, 1985).

I have mentioned these limitations of I-0 when applied to pollution, not in order to dispute its relevance or applicability but rather to set it in perspective. There is little to be gained from overestimating the current usefulness of I-0 or from underestimating the conceptual and practical problems associated with setting up and working with I-0 models. However, a number of the current drawbacks should be overcome with the collection of additional data, the development of improved techniques of modelling the behaviour of pollutants and with advances in methods of valuation.

Input-Output Analysis: the Basic Model

I-0 makes it possible to analyse the structure of production in an economy by taking account of the interrelationships among the producing sectors. It has been described by its originator, Leontief, as, '... an adaptation of the neoclassical theory of general equilibrium to the empirical study of the quantitative interdependence between interrelated economic activities' (Leontief, 1966, p. 134). I-0 represents the structure of an economy in algebraic form via a set of simultaneous linear equations. They show how the output of each sector (or industry) is distributed between 'intermediate' output, sold to other sectors to be used up in their current production, and 'final' output, sold to final demanders for private or public consumption or for exports or to add to the capital stock.

The coefficients of these equations represent the specific characteristics of the economic structure and are usually derived from an input-output table. This depicts, in the form of a matrix, the flows of transactions between all the sectors over a given period, usually a year. The rows of the table show the distribution of each sector's output to the other sectors and to final demand. The columns show how each sector obtains from the other sectors the inputs that it requires for its own production. The sectoral disaggregation in the table can be considerable (several hundred sectors, for example) and is determined by data availability and the purposes for which the table is being prepared. Between 50 and 150 sectors is common.

The matrix of input-output coefficients is usually derived after making the simplifying assumption that the inputs to and the outputs from each sector are linearly related in fixed proportions, such that a t-fold increase in all inputs leads to a t-fold increase in a sector's output. For each sector, the inputs into that sector are divided by the sector's output, yielding a vector of coefficients relating inputs to outputs.

The algebra of the basic I-O model can be set out in the following way:

gross output = intermediate output + final output

$$
(1)\quad
\begin{aligned}
x_1 &= a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n + f_1\\
x_2 &= a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n + f_2\\
&\vdots\\
x_n &= a_{n1}x_1 + a_{n2}x_2 + \dots + a_{nn}x_n + f_n
\end{aligned}
$$

where x_i is the ith sector's gross output, a_{ij} is the amount of sector i's output used in the production of one unit of the jth sector's output, and f_i is the final demand for the ith sector's output.

Each input-output coefficient can be derived from the I-O table as:

$$(2)\qquad a_{ij} = x_{ij}/x_j$$

where x_{ij} is the amount of the ith input used by the jth sector. We can identify the matrix A of coefficients as:

$$(3)\quad A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

where, for example, the last column indicates that to produce a unit of sector n's output requires a_{1n} from sector 1, a_{2n} from sector 2, and so on. Equation system (1) can now be rewritten in matrix form:

$$(4)\qquad x = Ax + f$$

or, since gross output minus intermediate output equals final output,

$$(5)\qquad (I - A)x = f$$ where I is the identity matrix.

As long as the inverse of (I - A) exists, we can pre-multiply equation (5) by it to get the solution vector x:

$$(6)\qquad x = (I - A)^{-1}f$$

Thus for any given vector of final demands we can solve the set of simultaneous equations to find a consistent vector of gross outputs from each sector. Because of simultaneity the solution takes account not only of the direct requirements of each sector necessary to increase final output by a given amount but also of the indirect requirements. For example, an increase in households' demand for electricity requires not only extra inputs of coal or oil but also extra inputs (including more electricity) in order to enable that coal and oil to be produced, and so on.

Primary inputs can also be accomodated in the analysis. For example, coefficients of labour per unit of each sector's output can be calculated. They can then be attached to different output vectors to work out the employment consequences of various patterns of final demand. A similar fixed-coefficient approach is one of the ways of incorporationg pollution into an I-0 model, as the next section indicates.

Forecasting and Projecting Pollution in an I-0 Framework

Perhaps the simplest way of incorporating the generation of pollutants into an I-0 model is to add an extra row to the I-0 system for each pollutant, where each element represents the physical quantity of that pollutant emitted by that sector in a given time period (Leontief, 1970a). Then, extending the assumption of linearity to the relationship between each industry's output and the amount of pollutant emitted, coefficients of pollutant per unit of industry output can be calculated. The augmented I-0 model can then be solved to find not only the gross output of each sector consistent with a given vector of final demands but also the quantities of given pollutants emitted by each sector in order to produce that sector's output. This approach is clearly applicable to emissions of CO_2 and sulphur oxides from the combustion of fossil fuels.

The augmented I-0 system can be used to explore a variety of possibilities. A first approach might be to forecast outside the model what will happen to final demand over a given time-period and then use the model to forecast the consequent levels of gross output and pollution. This could be done on the assumption that past trends in final demand would continue unchanged and that technology would remain unaltered. A further question which might be investigated would be to find, out how many years it might take, given current growth rates of final demand and output, to achieve particular levels of emission or concentration of CO_2 or sulphur oxides.

The assumption of unchanging technology is too simplistic, however, and it would make more sense to change the technical coefficients, and also the pollution generation coefficients, in line with known trends. The solutions could then be recalculated and would be expected to lead to new levels of output and pollution emission. A variety of scenarios could be investigated on the basis of a range of assumptions about final demand and technology, themselves based on analyses of demographic and technological trends. It is hardly necessary to point out that such analyses and the associated forecasts are subject to errors which tend to increase with the length of the time-period considered.

It is important that the classification of the sectors in the I-O table is appropriate to the problems which are being investigated. This can be a problem because I-O tables are not usually prepared with environmental analysis as a priority (or even a consideration) and so are likely to aggregate industries with significantly different pollution characteristics (Kohn, 1975, p. 348).

Because CO_2 and sulphur oxides are particularly associated with energy use and the burning of fossil fuels, it is especially important that the energy sectors be disaggregated and analysed appropriately. I-O models have been extended to incorporate a detailed and specific analysis of energy sectors (Bullard and Herendeen, 1977; Denton, 1977; Hoch and Carson, 1984; Herendeen, 1974; Park, 1982; Reardon, 1973) and there is good reason to combine this with the analysis of pollution (Muller, 1979; Pearson, 1984).

At another level of aggregation, the regional nature of the pollution problem has to be considered in the design of the model because, on the one hand, a number of pollution problems are best analysed at a local rather than a national level, while on the other, there are aspects which need to be analysed at a multi-regional or even global level. SO_2 and CO_2 provide good examples of these different aspects, for while the effects of these pollutants vary locally, their generation and transport can occur at a continental scale. Input-output analysis has in fact been carried out for pollution generation at both regional and multi-regional levels (Kohn, 1975, and Leontief et al., 1977, are good examples of these two levels).

Turning now to the specific problems posed by CO_2, the use of I-O to investigate issues related to CO_2 and the greenhouse effect represents a challenge of considerable complexity. To the extent that increased concentrations of CO_2 produce climatic change, including changes in temperature, there will be impacts on both the level and pattern of final demand (for heating, cooling, clothing and food, for example), on agricultural productivity and the productivity of other sectors, on energy requirements in particular and on interregional and international trade.

Is there any way in which these effects might be explored with I-0? Yes, because it would be possible in principle to experiment with different mixes of final demand and with different sets of I-0 coefficients. The consequent changes in the levels and patterns of output and pollutants could then be investigated. Of course, the really difficult economic part in all this would be to predict how the mix of final demand and sets of input-output coefficients would change in response to any given set of predicted physical consequences of a greenhouse effect.

To summarise this section, it is clear that I-0 has the potential to be used effectively to forecast or project a variety of pollution scenarios, provided that data is available in the appropriate form and at the appropriate scales.

We turn now to control strategies and to how I-0 can be used to model them.

Control or Abatement Strategies

These are strategies that reduce the generation or the discharge of pollutants. There is a wide variety of possible strategies here, including the following, none of which need be mutually exclusive:

a) Influencing the level and pattern of final demand; for example, a low growth scenario of the type often proposed in the early 1970s. Such a policy might be specifically targeted at the energy sectors or at particular energy or other sectors that are the most polluting (or rather, whose damage is considered most serious).

b) Influencing the discharge of pollutants by treating them; for example, scrubbing stack gases.

c) Changing the mix of technologies used for specific purposes; for example, changing to a mix of energy technologies that produce less (or at least different) pollutants. Possibilities here might include changing from high to low sulphur coal, or moving from heavy dependence on fossil fuels to nuclear, hydro, wind or wave-generated electricity to reduce CO_2 or SO_2, although the latter may bring their own environmental repercussions (for example, the problems of nuclear waste). Another important option is energy conservation.

There are two broad approaches to investigating these strategies. The first is simply to set certain objectives, such as air quality standards, and to try out a variety of ways of meeting them. The second approach is to set the analysis within a framework of optimisation where, for example, the aim might be to achieve given standards by choosing that mix of abatement techniques which minimises the cost of meeting the targets. I-O analysis on its own is not set in this kind of optimising framework and so appears more suitable for the first approach. However, when combined with linear programming (LP) it can be used for the second.

Control Strategies without Optimisation

The first possibility, influencing the level and pattern of final demand, is probably the easiest to investigate. We could, for example, try out a low growth scenario by projecting low rates of growth in all sectors or in a particular sub-set of sectors. The advantage of the I-0 method here is that it allows us to investigate not only the direct but also the indirect consequences of a new pattern of final demand. Thus, the ultimate changes in the discharge of pollutants are fully consistent in a way in which they would not be without this kind of general equilibrium approach; an approach which allows the complex repercussions of exogenous changes to work their way through the entire system.

More generally, it is possible to obtain direct plus indirect pollution-output coefficients (or 'intensities') for any pollutant by multiplying the vector of direct pollution-output coefficients by the inverse matrix from the I-0 model. The direct plus indirect coefficients indicate, for one unit of final demand in any given sector, how much of the pollutant is emitted directly and indirectly in all sectors. Examples which include sulphur oxides are to be found in: Victor (1972), for Canada; Leontief and Ford (1972), for the USA; and Miernyk and Sears (1974), at a sub-regional level, for West Virginia, USA.

The direct plus indirect coefficients can be used to investigate the pollution intensity of different patterns of final demand. For example, Victor (1972, pp. 200-209), using both a linear programming model to minimise the 'ecologic cost' of satisfying a given final demand vector, and a straight I-0 model, examined the implications for his 'index of ecologic cost' if private car use in Canada were reduced by 50 per cent and replaced by public transport. The consequences of the estimated new final demand vector in the I-0 model (with changes in petroleum products, vehicles and parts, rubber products, distributive services and transportation) were an 8 per cent decline in ecologic cost, with the change in the final demand for petroleum products accounting for most of this.

A potential application, which relates to proposals such as low growth strategies, 'soft' energy paths and alternative lifestyles, might be to estimate the direct plus indirect pollution intensities per unit of consumption spending by different income or population groups. This would indicate the ways in which different income levels, lifestyles and consumption patterns result in differences in the environmental implications associated with satisfying these final demands. It would also permit the investigation of the implications of alternative distributions of income or expenditure for the emission of pollutants. Such information would be helpful to the framing of a variety of social and economic policies. A version of an I-0 model that could handle this kind of estimation can be found in Pearson (1984).

The second possible pollution control strategy, that of abating pollution through the treatment of the residuals of production and consumption processes is one which has been widely explored. Leontief (1970; see also 1973, 1974) proposed the extension of the I-O model by adding columns to represent pollution reduction processes, as well as rows to represent pollution generation. The augmented model can then be used to investigate the generation and abatement of pollution under a variety of assumptions about final demand, technological possibilities and environmental quality standards.

This model has been applied. In an ambitious project, Leontief et al. (1977) undertook the task of estimating a multiregional world model (with 15 regions) that included pollution generation and abatement. The model is based on 1970 and investigates a variety of scenarios for world development for 1980, 1990 and 2000. Not surprisingly, however, there were serious data availability problems with the pollution generation and reduction sectors, particularly for the less developed regions of the world. Thus, in some cases proxy data had to be used because, 'No information exists, for example, on the costs of pollution abatement for medium or low-income countries.' (p. 25). The grand scale of this project makes the model seem potentially appropriate for investigating a problem like the discharge of CO_2, although Leontief and his team did not try to do this. In fact, particulates were the only category of air pollution included in the study. Whilst admiring the attempt to estimate this mammoth model, it is difficult not to be disturbed by the scarcity of real pollution data. There is a temptation with such models to forget rather quickly the wide margins of error that inevitably surround their predictions.

There is one aspect of pollution abatement to which Leontief's (1970a) paper drew particular attention. This is that pollution abatement itself can cause additional pollution because it requires inputs which in turn require other inputs, all of whose production can generate additional pollution. For example, the equipment needed to clean polluted air may require electricity, whose generation then creates further pollution. There is thus an empirical question as to whether significant amounts of pollution are created by different types of pollution abatement activities. If they are, then this is something that has to be taken account of when framing policy. Since this is essentially an empirical question, there is no universal answer. However, one study (Kohn, 1975) estimated the size of the so-called 'Leontief effect' in a model of the St Louis airshed, using a regional I-O table, and found that it added only about 2 per cent to the cost of achieving maximal allowable concentrations of five pollutants. This contrasts strikingly with the hypothetical example in the original Leontief (1970a) article, where the additional cost of meeting a set of standards was 13 per cent, i.e. the 'abatement multiplier' was 1.13. I shall return to this issue later, in a further discussion of Kohn's paper.

One of the uses which has been made of I-O models with pollution abatement activities included is, as has been indicated, to calculate the cost of abatement. The world study by Leontief et al. (1977)

estimated the costs of achieving a variety of abatement standards, in terms of the total current plus annualised capital costs of abatement procedures as a percentage of gross domestic product. For regions in which the 1970 standards of pollution abatement were to be applied, the total costs of all abatement activities were in the range of 1.4 to 1.9 per cent of gdp, while the share of the capital stock used for abatement purposes was between 2.5 and 4 per cent. As pointed out earlier, however, these results need to be treated with some caution.

A different study of the costs of meeting pollution standards is that of Miernyk and Sears (1974). The aim of the study was to investigate what effects compliance with the U.S. Clean Air Act of 1970 would have on programmes intended to stimulate regional development in the USA. The work was based on a dynamic regional I-0 model for West Virginia. The model has the following structure:

(7) $$x_t = A_t x_t + D x_t + B(x_t - x_{t-1}) + f_t$$

where: x_t is a vector of output in period t; A_t is the matrix of I-0 coefficients for each year; D is the matrix of (constant) replacement capital coefficients; B is the matrix of (constant) expansion capital coefficients; and f_t is the final demand vector in year t. The equation can be rewritten as:

(8) $$(I - A_t - D - B)\, x_t + B x_{t-1} = f_t$$

and, when solved for annual output, yields:

(9) $$x_t = (I - A_t - D - B)^{-1}(f_t - B x_{t-1})$$

The first step was to make projections of output levels for 1975 that were not constrained by the cost of meeting air pollution abatement standards. Then, having collected data on the cost of installing and operating pollution abatement equipment for the major industrial air polluters in West Virginia, Miernyk and Sears adjusted the elements of the basic matrices in the I-O model to reflect the extra costs of complying with prescribed emission standards for particulates and sulphur dioxide.

The direct and indirect costs of compliance were estimated in two stages. They prepared and solved the system:

$$(10) \qquad x'_t = (I - A'_t - D' - B')^{-1}(f_t - B'x_{t-1})$$

where the primes indicate that the matrices have been modified to reflect the capital and operating costs of abatement. What are then called the 'real' costs of abatement were derived by solving:

$$(11) \qquad x^*_t = (x'_t - f_t) - (x_t - f_t)$$

where x^*_t indicates the extra production required to produce a constant vector of final demand when all establishments have complied with 1970 pollution abatement requirements.

The study showed that for effective compliance with the standards, the increase in total gross output was 4.3 per cent. The authors concluded that although the cost increases implied by compliance were too large not to be passed on to consumers via higher prices, this would not place West Virginia industry at a competitive disadvantage, as long as compliance standards remained national and did not vary by location or establishment.

I have dwelt at some length on this study, for two reasons: firstly, because it is an admirable example of Miernyk's usual clarity of exposition; and secondly, because it is a good illustration of the importance of using a dynamic I-0 model where significant changes in the capital stock are involved.

A further application of the I-0 model to the costs of abatement involves making use of the system of price equations that underlies the I-0 system. For example, it is possible to estimate the impact on the prices of all sectors' outputs of making individual sectors pay all or part of the cost of reducing pollution (Leontief, 1970a). One recent application is by Ketkar (1984), who uses an I-0 model to investigate the impact on prices, incomes and employment of two policies for meeting pollution standards in the USA. The policies compared are those of using regulations, on the one hand, and taxes and subsidies, on the other. In contrast with Leontief's approach, however, Ketkar does not have additional rows and columns for pollution generation and reduction. He says (p.238), 'It is difficult to make this approach operational because the output of pollution either in the aggregate or at the level of each industry is unknown. An alternative procedure is to adjust the interindustry direct coefficients table for pollution abatement costs in various industries.' This procedure is similar to that of Miernyk and Sears.

Ketkar found that the effect of meeting U.S. controls on pollution in the early 1970s was to raise prices on average by 1.4 per cent. However, much bigger price increases occurred, not surprisingly, in the major polluting industries, ranging from 3 per cent to more than 12 per cent.

Ketkar also estimated the impact on the level and distribution of incomes of meeting the controls, using a semi-closed I-0 system based on Miyazawa's (1976) approach. This closes the loop between personal incomes generated in production and incomes spent on consumption (see also Pearson, 1984). Ketkar finds that the pollution control expenditures generate substantial amounts of extra income and jobs and lead to increases in gross output in most industries.

Ketkar's work is a good example of the kinds of analysis that can be done on pollution abatement strategies. Clearly this type of work can be useful in the choice of particular abatement strategies. However, as Pearce (1976) points out, to be properly helpful with policy choice the I-0 models need to be set in a framework of effective cost-benefit analysis. This is something which has not yet been achieved partly because of problems of valuation and partly because of problems of aggregating values. Victor (1972) produced a set of relative social weights for his 'ecologic commodities' but his procedure for obtaining them (asking a well-informed colleague) not surprisingly failed to command Pearce's full approval. That Victor, whose work was generally painstaking and thorough, resorted to this tactic, is a good illustration of the difficulties of valuation.

The third possible control strategy mentioned above was that of changing the mix of technologies. For example, the policy might involve changing from heavy dependence on fossil fuels to alternative sources of electricity generation, or changing the mix of fossil fuels themselves. Here it is necessary to provide appropriate estimates of the coefficients for the alternative sectors. Once this is done, the impact of the new mix on output, prices, employment and pollution can be estimated. Miernyk and Sears (1974), for example, simulated three processes of converting coal to gas for use in electricity generation. An interesting feature of the work is that it traces the time-phasing of the investment impacts resulting from the construction of a major gasification-generation complex, by using a dynamic I-O model in its 'dynamic inverse' form (see Leontief, 1970b).

Control Strategies in a Framework of Optimisation

I now want to discuss an approach which involves optimisation. Effectively, what it does is to enable us to investigate the cost-effectiveness of different strategies for achieving predetermined sets of environmental quality targets in the form of emission standards. A good example is the work of Kohn (1975), which combines linear programming and regional I-O analysis in a study of the control of five separate air pollutants in the St Louis airshed in the U.S.A. Kohn takes account of Leontief's argument that the inputs required by antipollution activities themselves generate further production in other sectors with consequent further emissions of pollution. This is the main reason why he uses I-0 analysis. 'In contrast with Leontief, however, Kohn recognises that there are many processes for controlling pollution and that they need not be combined in fixed proportion across all production activities,' (Ahmad, Dasgupta and Maler, 1984, p.323).

In Kohn's model the maximum allowable flows of five separate pollutants are first specified. Then a set of air pollution control method activity levels is selected which meets the allowable pollution flows at least cost, subject also to achieving specified levels of industrial output in the polluting sectors themselves. The efficient set of control methods is, 'that set which eliminates excess pollution, including the incremental pollution associated (directly and indirectly) with pollution control itself, at the least cost ... ' (Kohn, 1975, p.326). Kohn considered 94 polluting sources (e.g. steel plants, electric power stations) and 309 alternative control methods. Kohn finds that the result of incorporating the input-output feedbacks to the vector of polluting activities is to alter the optimal set of control methods as compared with the situation where the feedbacks are not allowed for. This kind of substitution is ruled out of the standard Leontief approach which is based on fixed technological relationships. Moreover, Kohn's model effectively allows for increasing costs per unit of pollution control, where the straight I-0 model does not. As I pointed out earlier, however, Kohn finds that the 'abatement multiplier' which allows for the feedback from pollution abatement activities on the flow of emissions, is small, increasing abatement costs by only 2.3%.

It is significant, however, that Kohn finds that 60% of the feedback impact could be captured by incorporating only the direct inputs to pollution control activities. He, therefore, questions whether the computational effort of estimating the indirect inputs and consequent emissions through the additional use of the I-0 table is justified. If Kohn's results are supported by other studies, it may be that in many cases simpler calculations than those involving I-0 will suffice, as Peterson (1984, p.353) suggests. However, we should be wary of rushing to this conclusion until such evidence has been accumulated, because the size of the feedback effect could vary considerably, depending on both the types of pollutant considered and the abatement processes used.

Kohn also challenges the plausibility of treating air pollution control as a constant cost industry, pointing out that there are significant capacity constraints on pollution control processes when pollution control occurs at the source. The result would be rising marginal costs of control. He suggests that, 'If, because of increasing costs, it is not feasible to incorporate pollution control sectors in input-output models, it may be that future research relating economic activity and pollution control costs will depend on interfaced input-output and cost-effectiveness models such as the one presented in this paper,' (Kohn, 1975 , p.348).

Any linear programming model solution yields shadow prices, indicating the change in the value of the objective function which would result from a relaxation in the constraints. In Kohn's model, the shadow prices for pollutants indicate the increase in the total cost of abatement associated with a decrease of one pound in the corresponding allowable annual emission flow. When estimated from the combined linear programming/I-0 model the shadow prices indicate the pollution control costs in the St Louis airshed associated with a one dollar increase in sales by the corresponding economic sector. These costs reflect the fact that an increase in final demand in any given sector increases the production levels and hence the pollution levels of other sectors. Another interpretation of the shadow prices is, of course, that they provide estimates of emission fees or charges which would theoretically achieve the optimal control solution through decentralised decision-making rather than regulations.

There are other models apart from that of Kohn, which combine linear programming and I-0, and for the reasons suggested earlier this looks to be a potentially fruitful line of approach. One example of such a model is the Rosenbluth model used by Victor (1972) for Canada. Victor uses this alongside a more standard I-0 model, allowing an interesting comparison of results. Another more recent and very useful study is that of Muller (1979), which uses both linear and non-linear programming with an interregional I-0 model that also incorporates a multiple source dispersion model.

Assessment

The usual justification for using input-output analysis despite its drastic simplifications, comes from its ability to model general equilibrium among all the interrelated sectors of a national or regional economy in a consistent manner. When it comes to analysing the emission and control of pollutants these advantages are still apparent but we need to ask whether I-0 copes well with the particular issues and problems raised by the analysis of pollution.

First, linearity: it is clear that to represent the processes of pollution emission and especially abatement as linear is an analytical simplification, the gains from which need not necessarily outweigh the losses. But there is no reason in principle or in practice why the emission of pollutants should not be related to production in a non-linear fashion, even though the linear I-0 model is retained to analyse the production relationships. Pollution abatement is perhaps more of a problem. Leontief's use of separate pollution control sectors with constant costs has been challenged by Kohn and others. However, Muller (1979) has presented a non-linear programming model with solution algorithm, allowing for increasing marginal costs of pollution abatement, so it is clear that non-linear pollution abatement processes can be and probably should be accommodated.

A further issue is whether the use of I-0 justifies the cost of doing so. As we have seen, Kohn even wonders whether the extra computational effort and data problems of adding I-0 to his linear programming model are worthwhile, in view of the limited extra information that is yielded after allowing for the indirect effects of pollution abatement. However, much more work is needed before it can be confidently confirmed or denied that this generally the case for all pollutants in all economies. Moreover, the estimation of the indirect feedback effects of pollution abatement is by no means the sole (or even the major) justification for using I-0 in the analysis of economic issues connected with pollution. The more general reasons for using I-0 remain valid.

The partial coverage of I-0 and environment models has also been rightly criticised, in the sense that only a limited set of pollutants is often considered and the inputs from the natural environment are rarely accounted for (except, for example, in the work of Victor (1972) and to a limited extent by Leontief et al. (1977)). There have been few attempts to follow the undoubtedly demanding 'materials balance' approach (Kneese, Ayres and D'Arge, 1970). Again the issue of the costs and benefits of model complexity arises. Another question of coverage is the fact that most I-0 models do not attempt to pursue the impact of pollutants on particular locations and to trace the damage that they do. Whilst such modelling techniques do exist, they tend not to be used with I-0. One significant exception is the work of Muller (1979), which demonstrates clearly the usefulness of modelling the disperson of pollutants after they have been emitted. Further work is needed in this area, to link I-0 and dispersion and damage models.

If the damage done by pollutants is not pursued, it follows that the value to society (or to other societies, in the case of transfrontier pollution) of the losses incurred is also not being estimated. In the absence of such (undeniably difficult) estimates the analysis of pollution control strategies cannot be set in a proper cost-benefit framework, even though many of the costs of pollution control can be estimated through the I-0 equations. However, these problems of valuing environmental damage are by no means specific to I-0 analysis. Their solution requires the development of improved conceptual and empirical approaches to valuation.

Turning now to the question of data availability, the data demands of I-0 are always considerable and this is especially so when I-0 is extended to incorporate pollution. This is partly because of the need for detailed information about pollution emission and abatement at a sectoral level, and partly because of the need to use regional or multi-regional I-0 tables. To a considerable extent, of course, the collection and availability of data on pollution depends on the seriousness with which the environmental issues are perceived and on the political will to investigate problems and policies. Acid rain provides a good example of this point.

However, all of these reservations need to be seen in perspective. When combined with other techniques, such as linear or non-linear programming, I-0 can help us explore a limited but none the less important range of questions about pollution. With sulphur dioxide in particular, the I-0 approach seems potentially very helpful and a number of studies have already taken account of it in various ways, as we have seen. Further work should built on what has already been done, but it does need to include dispersion and damage. The current political controversy over acid rain points up the need for more and better work in this area, particularly on the issue of the economic implications of alternative control strategies.

With carbon dioxide there must be much more doubt about the current usefulness of I-0, not least because of the relatively long time-frame in which the analysis needs to be set, the complexity of the repercussions, and the uncertainties surrounding potential climatic changes and their consequences. The current lack of scientific consensus on many aspects of carbon dioxide and the simultaneously global and local nature of much of the economic modelling required, suggest that there will be considerable difficulties in constructing and using I-0 models effectively in this area. Nevertheless, if effective economic modelling of carbon dioxide and the greenhouse effect is to be carried out, it is likely that I-0 analysis will sonner or later confirm once again its usefulness as a workable tool of general equilibrium analysis.

Acknowledgements

I would like to thank Sophie Bowlby (University of Reading) and David Hawdon (University of Surrey) for helpful discussions on this topic.

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