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quantity of commercial sulfuric acid production in the airshed, the abatement multiplier would decline to 1.011.[30]

Increases in sector production, GHx_0

As a consequence of the direct demand for inputs, Hx_0, there are secondary or derived demands as well. The equilibrium set of increased activity levels, GHx_0, is presented in table 6. Note that it requires $54.1 million in increased production levels to supply the $24.1 million of direct inputs for abatement. The $19.0 million increase in demand for household services suggests that pollution abatement could create employment for 2,500 people.[31]

A sensitivity test was performed to determine the relative significance of the *derived* demand for inputs on the size of the abatement multiplier. When the G matrix was omitted (or, in effect, replaced by a $[23 \times 23]$ identity matrix), the abatement multiplier declined from 1.023 to 1.014. While the feedbacks associated with indirect inputs account for less than half of the abatement multiplier, it can still be observed that the larger the input-output multipliers, the larger will be the abatement multiplier.

Increases in polluting activity levels, $FGHx_0$

The increases in pollution source levels, assumed proportional to increases in corresponding economic sector activity levels, are represented by a

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[30] Recovered sulfuric acid is valued at one-half to one-third the value of commercially produced sulfuric acid depending on whether it is a by-product of power generation (and relatively pure) or of lead smelting. Assuming a fixed dollar demand for sulfuric acid, it would take two to three tons of recovered acid to replace one ton of commercial acid production. This feedback effect was implemented by treating by-product sulfuric acid as a negative input independently of the chemical, petroleum, and rubber products sector. The savings in indirect inputs associated with a dollar reduction in the projected level of commercial acid production are then included as negative direct inputs. These include a reduced demand by sulfuric acid producers for labor, machinery, water, power, and elemental sulfur.

[31] This is based on the annual income per manufacturing employee in the St. Louis SMSA in 1967 (*1967 Census of Manufactures, Missouri*). This does not include any decreases in employment due to higher operating costs and prices. For a study of adverse impacts of abatement on employment, see Robert J. Kohn, "Labor Displacement and Air Pollution Control," *Operations Research* Volume 21 (September-October 1973): 1063–1070.

TABLE 6

Increased Indirect and Direct Economic Activities Associated With an Efficient Set of Air Pollution Control Methods in the St. Louis Airshed in 1975

(millions of dollars)

Economic Sector	*Increased Activity Levels* (GHx_0)
Food, tobacco, and kindred products	1.1
Textiles and apparel	.2
Lumber and furniture	.1
Paper and printing	.4
Chemicals, petroleum, and rubber products[a]	.6
Leather products	[a]
Stone, clay, and glass	.1
Primary metals	.4
Fabricated metals	.1
Nonelectric machinery	6.9
Electrical machinery	.1
Transportation equipment	9.1
Miscellaneous manufacturing	.1
Agriculture	.1
Mining	−13.3
Construction	.3
Transportation, communication, and utilities	18.5
Wholesale trade services	.5
Retail trade services	2.9
Finance, insurance, and real estate	3.0
Business, personal, and other services	2.6
Households	19.0
Local government	1.3
Total of all sectors	54.1

Note: The $11.9 million in sales of recovered sulfuric acid, a by-product of pollution control, are not included in this table.

[a] Less than $50,000.

(94 × 1) matrix product, $FGHx_0$. Selected elements of this matrix product are contained in table 7.[32] It will be observed here that the largest per-

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[32] Some of the values in table 7 can be checked by the reader. The increased combustion of gasoline in automobiles and light duty trucks (row 1) is the product of the f_{ik} coefficient, 643,520 gallons, in table 3 (row 1, column 19) and the equilibrium increase in the value of retail trade services in table 6, $2.9 million. (The discrepancy in results is due to rounding.) The increase in the combustion of coal in pulverized coal furnaces equipped with electrostatic precipitators (see row 3, table 7) is verified by multiplying

TABLE 7

Estimated Production Levels for Selected Pollution Sources and Increases in These Levels Associated with an Efficient Set of Air Pollution Control Methods in the St. Louis Airshed in 1975

Pollution Source	*Estimated Production or Consumption Level for 1975*	*Increase Because of Pollution Control* ($FGHx_0$)	*Percentage Increase*
(1) Combustion of gasoline in automobiles and light duty trucks	1,137,000,000 gallons of gasoline	1,841,000 gallons of gasoline	.2
(2) Diesel fuel used by railroads	40,800,000 gallons of fuel	385,000 gallons of fuel	.9
(3) Combustion of coal by industry in pulverized coal furnaces equipped with electrostatic precipitators	583,000 tons of coal	625 tons of coal	.1
(4) Combustion of coal in residential stokers	428,000 tons of coal	1,330 tons of coal	.3
(5) Combustion of coal at the Meramec Power Plant	730,000 tons of coal	10,330 tons of coal	1.4
(6) Combustion of coal at the Labadie Power Plant	5,500,000 tons of coal	77,840 tons of coal	1.4
(7) Refuse burned in municipal incinerators	357,000 tons of refuse	405 tons of refuse	.1
(8) Grain handled and processed in elevators	2,400,000 tons of grain	2,110 tons of grain	.1
(9) Crude oil processed in refineries	137,606,000 barrels of crude oil	50 barrels of crude oil	[n]
(10) Rock and gravel crushed, screened, conveyed, and handled	4,000,000 tons of rock	1,225 tons of rock	[n]

[n] Less than .05%.

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the f_{ik} coefficients in row 3 of table 3 by the corresponding sector increases in table 6 and summing. To verify the increased coal combustion at the Meramec Power Plant, the corresponding f_{ik} coefficients in row 4 of table 3 and sector increases in table 6 are multiplied and summed. However, the coefficient in row 4, column 17 must be multiplied by the product of $3.17 million (the value of direct electrical inputs for pollution control in the feedback model) and the transportation, communication, and utilities sector self-multiplier, 1.2178 (see table 2). This special case is explained in footnote 26.

centage increases are for the power plants which supply the electricity needed for pollution control.

The percentage increases in pollution source levels are substantially less than the 2.3 per cent increase of Z' over Z. Essentially, this is because a portion of emissions associated with the original pollution source levels is allowable, whereas all emissions associated with the increased levels must be eliminated. However, the comparatively small percentage increases in table 7 help to explain why the abatement multiplier in the present study is as small as it is.

Additional emissions, E^*FGHx_0

The increase in air pollutants associated with the vector of increased pollution source levels, $FGHx_0$, is found by premultiplying the latter by a $(P \times M)$ matrix, E^*. The element, e_{ij}^*, of this matrix is the emission flow of pollutant i per activity unit of control method, j, where j is the existing or base year control state for pollution source j. The E^* matrix is contained in the E matrix and is used here for explanatory purposes only. These incremental emissions, elements of the (5×1) matrix product, E^*FGHx_0, are contained in table 8. It is not surprising that the largest percentage increases in the pollution reduction requirements are for nitrogen oxides and sulfur oxides, which are the major pollutants from the larger power plants in the St. Louis airshed. As noted earlier, the most significant impact of pollution control will be the increase in power generation.

The percentage increases in required emission reductions, which range from .3 to 2.1 per cent, are less than the 2.3 per cent increase in abatement costs (of Z' to Z). This is in contrast to the Leontief example, where the cost of pollution abatement increases by the same per cent as the increase in the quantity of pollution which must be eliminated. Because pollution control is represented by Leontief as a constant cost industry, the marginal cost of eliminating one gram of pollutant does not change. In the present model, the cost of abatement increases more than the pollution reduction requirements because of increasing costs. This would not have been the case if each of the nonzero control method activity levels had increased by the same proportion (see table 4). Because of the rising cost of pollution control, the abatement multiplier is larger than it would otherwise be.

Summary of factors which affect the size of the abatement multiplier

The abatement multiplier has been introduced as a device by which to measure the feedbacks of pollution abatement on the flow of emissions. It

TABLE 8

Projected Emissions in the St. Louis Airshed in 1975 in the Absence of Additional Abatement, Allowable Emissions, and Incremental Emissions from Pollution Control

(emissions in millions of pounds)

Pollutant (1)	*Projected Emissions in 1975 in the Absence of Additional Abatement* (2)	*Allowable Annual Emission Flows*[a] (3)	*Required Reductions in Emission in 1975* (4)	*Incremental Emissions Because of Abatement* (E^*FGHx_0) (5)	*Percentage Increase in Required Reductions* (6)
Carbon monoxide	4202.2	2335.2	1867.0	6.1	.3
Hydrocarbons	1518.8	994.5	524.3	2.3	.4
Nitrogen oxides	415.4	303.5	111.9	2.4	2.1
Sulfur dioxide	1389.6	400.4	989.2	11.3	1.1
Particulates	299.6	135.8	163.8	.9	.5

Note: Emissions from stacks higher than 600 feet are adjusted down to ground level equivalent emissions.

[a] The allowable flows are based on the following air quality goals (annual averages at the St. Louis Continuous Air Monitoring Program Station): carbon monoxide, 5.0 ppm; total hydrocarbons, 3.1 ppm; nitrogen oxides, .069 ppm; sulfur dioxide, .02 ppm; suspended particulates, 75.0 $\mu g/m^3$.

can be concluded from the above analysis that the abatement multiplier is larger:

(1) the greater the portion of pollution control costs which represent current direct purchases of inputs;

(2) the less the replacement of existing production by recycled pollutants;

(3) the larger the input-output multipliers;

(4) the larger the ratios of polluting activities to sector levels (the less a region imports the larger these ratios will be);

(5) the greater the emissions associated with polluting activities;

(6) the more steeply rising are the costs of pollution abatement.

It should be stressed that this study of the abatement multiplier is based on a specific model of a specific airshed. Any conclusions must be viewed as tentative because they may be sensitive to parameters and data unique to the particular model. It is likely, however, that the cost of pollution abatement and the optimal set of control method activity levels are more sensitive to factors other than the abatement multiplier. There are important cost and emission parameters in the model which are only estimates. These include data which characterize the technologies for desulfurizing power plant stack gases and controlling nitrogen oxides from automobiles. Relatively small changes in these would have a more substantial impact on the optimal solution than do the abatement feedbacks. In addition, minor changes in certain air quality goals or in the formulas which describe the relationship of emission flows to pollutant concentrations would have a more important impact on the control solution.

It is not clear whether the size of the abatement multiplier might not also be sensitive to such changes in parameters. One such sensitivity test was performed. The allowable emission flows (see table 8, column 3) were reduced 10 per cent for each pollutant in the model. The new values of Z and Z' were respectively \$55.5 million and \$56.7 million. While this test confirmed the increasing costs of pollution abatement, the abatement multiplier changed very little, and in fact, declined slightly.[33]

Although the value of 1.023 for the abatement multiplier for the St. Louis model appears to be small, it should be noted that the incremental control costs of \$.8 million are 1.5 per cent of the sum of incremental economic activities, which would be \$54.1 million. In contrast, the total cost of abatement from this model is only .1 per cent of the projected total value of economic activity in the St. Louis region in 1975. Thus the ratio of control costs to economic activity is far greater at the margin than are the corresponding totals. It is apparent that the assumption of fixed maximum allowable pollution flows implies that increased economic activity will require significantly higher expenditures for environmental control.

Results: Shadow Prices

The pollutant shadow prices presented in table 9 indicate the increase in the total cost of abatement associated with a decrease of one pound in the corresponding allowable annual emission flow. The pollutant shadow

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[33] The decline in the multiplier should not be too surprising. None of the first five factors which explain the size of the abatement multiplier are necessarily related to the level of abatement. Although the marginal costs of pollution control are likely to increase as abatement levels are increased, they could, in a linear programming context, be fairly constant for any specific small range equal to E^*FGHx.

TABLE 9

Shadow Prices Generated by the Linear Programming Models

Constraints	*Shadow Price in the Original Model*	*Shadow Price in the Feedback Model*
	Pollutants	
Carbon monoxide requirement	$.00428 per pound	$.00432 per pound
Hydrocarbon requirement	.02476 per pound	.02482 per pound
Nitrogen oxides requirement	.32639 per pound	.33333 per pound
Sulfur dioxide requirement	.02193 per pound	.02220 per pound
Particulate requirement	.07748 per pound	.07941 per pound
	Inputs from Input-Output Sectors	
Chemical, petroleum, and rubber products sector	0	.01811 per dollar
Nonelectric machinery sector	0	.01110 per dollar
Transportation equipment sector	0	.00494 per dollar
Mining sector	0	.01236 per dollar
Transportation, communication, and utilities sector		
Electricity only	0	.17132 per dollar
Natural gas, etc.	0	.01422 per dollar
Household sector	0	.01423 per dollar

prices from the feedback model incorporate the incremental pollution control costs associated with abatement. To the extent that control costs in the model correspond to control costs that would be borne by polluters, these shadow prices functioning as emission fees would theoretically achieve the optimal control solution x_0 via decentralized decision making.[34]

The merger of linear programming and input-output analysis produces the unique set of shadow prices at the bottom of table 9. These indicate the pollution control costs in the St. Louis airshed associated with an increased production of $1.00 by the corresponding economic sector.[35] If

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[34] The reader who is interested in calculating the government revenue from these emission taxes can multiply the rates in table 9 times the corresponding allowable flows in table 8. He may be surprised to find that the total annual revenue is more than four times the annual cost of abatement.

[35] The shadow prices for inputs were obtained as follows. The constraint, $[U - FGH]x = s$, was incorporated in the model in two equations, $Ux - FGy = s$ and

for example, the chemical, petroleum, and rubber products sector would increase its sales by $1.00, pollution control costs in the airshed would rise by 1.8 cents. The sale of an additional dollar of electricity would increase control costs by 17 cents.[36] A dollar increase in annual sales by the transportation equipment sector, which imports a large per cent of its inputs, would raise total costs of abatement in the airshed by half a cent. These costs reflect the fact that final demand sales by any sector increase the production levels of other sectors.

The shadow prices of the inputs have a second interpretation. If the pollutant shadow prices were used as emission fees, an increased production of $1.00 by an economic sector would involve incremental control costs and emission fees in the airshed equal to the shadow price.

Implications of This Research for Cost-Effectiveness Models for Environmental Planning

Abatement feedbacks

It is appropriate that the feedbacks of pollution abatement on the levels of polluting activities be included in cost-effectiveness models. Not only is the cost of abatement higher because of these feedbacks, but adjustments in the control solution may result. This was illustrated in this paper by the revisions in the optimal control method set (table 4) when feedbacks were incorporated.

While the inclusion of input-output multipliers improves the model, there is some question as to whether the increased accuracy is sufficient compensation for the immense computational effort involved. It was observed in this paper that 60 per cent of the feedback impact could be captured by incorporating only the direct inputs and not the indirect inputs to abatement (i.e., by omitting the G matrix).[37] Moreover, a substantial

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$Hx - y = 0$, where the elements of y are values of direct inputs for abatement supplied by the separate economic sectors. The shadow prices of the elements of the null vector represent the incremental cost of abatement associated with a dollar increase in sales for the corresponding economic sector.

[36] Alternatively, the additional cost of abatement associated with the sale of one kilowatt hour of electricity to industrial, commercial, or residential customers would be .18 cents.

[37] It should be noted that the shadow prices for the inputs (see table 9) may in some cases be largely attributable to multiplier effects. If, for example, derived demands are excluded from the model (this is the case where the G matrix is omitted), a dollar in sales by the nonelectric machinery sector, would increase total cost of abatement by only .1 cents, far less than the 1.1 cents noted in table 9.

portion of the primary feedback could be incorporated through electricity inputs alone, thereby further simplifying the model.

If it were anticipated that large quantities of recovered sulfuric acid were to replace existing commercial acid production, it would be advisable to incorporate this abatement feedback into a cost of control method. The present research suggests that certain inputs have a more significant feedback effect than do others, and that the latter might, for simplicity, be ignored.

Measurement units for pollution source levels

Emission factors are generally based either on inputs (i.e., tons of coal burned, gallons of diesel fuel consumed, etc.) or on outputs (i.e., tons of steel manufactured, number of airplane landing and take-off cycles, barrels of cement produced, etc.).[38] As a result, it is typical to measure polluting levels in terms of both inputs and outputs. This asymmetry, apparent in tables 1, 3, 4, and in the example used in the appendix, is in contrast to the uniformity found in input-output analysis.

Some thought should be given to expressing the levels of polluting activities in future cost-effectiveness models in terms of either inputs or outputs, but not both. If output units are used, the cost-effectiveness model could more readily be related to input-output tables as well as other data arranged according to a standard industrial classification. Although the possibility of basing pollution coefficients on output units would eliminate the need for the F matrix used in the present model, it would also increase the dimensions of the control method vector.[39]

Implications of This Research for Input-Output Models for Environmental Planning

Aggregation of economic sectors

One of the problems encountered in this research relates to the aggregation of industries in the input-output model. The aggregation of all utilities in a single sector required special handling to separate the very

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[38] See *Compilation of Air Pollutant Emission Factors* (Revised), (Research Triangle Park: Environmental Protection Agency, 1972).

[39] This has been done in Wassily Leontief and Daniel Ford, "Air Pollution and the Economic Structure: Empirical Results of Input-Output Computations," *Fifth International Conference on Input-Output Analysis*, Geneva, Switzerland, January 1971.

different impacts of natural gas and electricity purchases. The fact that the chemical and petroleum industries, both major sources of air pollution in the St. Louis airshed, were included in the same sector of Liu's input-output model was a distinct limitation. The input-output models being developed for environmental studies should avoid aggregating industries with significantly different pollution characteristics.

The pollution abatement sector

Leontief has expanded the input-output structure with an additional row for pollution output and an additional column for pollution abatement. The feasibility of treating air pollution control as a constant cost industry is challenged in the present paper. Whereas there are no capacity constraints on interindustry sales in an open input-output model, there are significant capacity constraints on pollution control processes *when abatement occurs at the source.*[40] Thus there are only so many underfeed stokers which can be converted from coal to natural gas, so many new automobiles which can be factory equipped with the latest pollution control equipment, etc. As these upper limits become binding, successive levels of abatement are attained at rising marginal costs. If, for example, the pollutant shadow prices for the original model (see table 9) were *average* costs, the cost of pollution control in the original model would be the vector product of these costs and the corresponding required reductions in pollutant emissions (see column 4 of table 8), or more than $90 million a year. This demonstrates the extent of increasing costs, for clearly, a substantial amount of pollution abatement would have to occur at much smaller costs than these shadow prices for the annual cost of abatement to be $35.3 million. 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.

Appendix: Numerical Illustration of the Model

To clarify the model, consider the following example with two pollution sources, three pollutants, four economic sectors, and five control meth-

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[40] This may be more applicable to air pollution than water pollution control.

ods. This hypothetical airshed contains two sources of air pollution; a steel mill producing 1,000,000 tons of steel a year and a power plant whose annual consumption of coal is 2,000,000 tons. The vector of polluting production levels is,

$$s = \begin{bmatrix} 1{,}000{,}000 \\ 2{,}000{,}000 \end{bmatrix}.$$

Desirable air quality can be achieved in this airshed if total annual emissions do not exceed 8,000,000 pounds of particulates, 40,000,000 pounds of sulfur dioxide, and 35,000,000 pounds of nitrogen oxides. The vector of allowable emission flows is

$$a = \begin{bmatrix} 8{,}000{,}000 \\ 40{,}000{,}000 \\ 35{,}000{,}000 \end{bmatrix}.$$

The steel mill currently emits 7 pounds of particulates, 13 pounds of sulfur dioxide, and 2 pounds of nitrogen oxides per ton of steel produced. These emissions occur in the operation of basic oxygen furnaces, blast furnaces, sintering machines, coke ovens, and during the combustion of fuel oil, natural gas, and coke oven gas. The power plant currently emits 3 pounds of particulates, 118 pounds of sulfur dioxide, and 20 pounds of nitrogen oxides per ton of coal burned. Thus annual emissions in the airshed are well in excess of allowable flows for all three pollutants.

The present state of control (x_1) at the steel mill includes electrostatic precipitators for the basic oxygen furnaces, primary cleaners for the blast furnaces, and dry cyclone collectors for the sintering operations. The present pollution control method (x_4) at the power plant is an electrostatic precipitator.

The alternative control methods for the steel mill are (x_2) high energy wet scrubbers for the blast furnace, which would cost an additional $.10 per ton of steel output, and (x_3) the high energy wet scrubbers for the blast furnace plus electrostatic precipitators for the sintering operations, which would add incremental costs of $.25 per ton of steel output. The alternative control method (x_5) for the power plant is a desulfurization process costing an additional $1.20 per ton of coal burned. The row vector of control method costs is, $c = [\$.00\ \$.10\ \$.25\ \$.00\ \$1.20]$. Each of the alternative control methods would be used in combination with the existing control method. However, because it is the *incremental* cost of pollution control which is being minimized, the existing control methods are, for convenience, assigned zero costs.

The alternative control methods for the steel mill reduce particulate emissions from 7 to 4 pounds per ton of steel for the first alternative (x_2) and from 7 to 3 pounds for the second alternative (x_3). The desulfurization process (x_5) would reduce emissions from the power plant to 2 pounds of particulates, 12 pounds of sulfur dioxide, and 16 pounds of nitrogen oxides per ton of coal burned. The matrix of emission factors is therefore,

$$E = \begin{bmatrix} 7 & 4 & 3 & 3 & 2 \\ 13 & 13 & 13 & 118 & 12 \\ 2 & 2 & 2 & 20 & 16 \end{bmatrix}.$$

The distributive matrix which equates the sum of control method activities for each pollution source to the production level of that source is,

$$U = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix}.$$

The linear programming model in standard form is,

$$\begin{array}{llllllll}
\text{minimize} & Z = \$.00x_1 + & \$.10x_2 + & \$.25x_3 + & \$.00x_4 + & \$1.20x_5 & & \\
\text{subject to} & x_1 + & x_2 + & x_3 & & & = & 1{,}000{,}000 \\
 & & & & x_4 + & x_5 & = & 2{,}000{,}000 \\
 & 7x_1 + & 4x_2 + & 3x_3 + & 3x_4 + & 2x_5 & = & 8{,}000{,}000 \\
 & 13x_1 + & 13x_2 + & 13x_3 + & 118x_4 + & 12x_5 & = & 40{,}000{,}000 \\
 & 2x_1 + & 2x_2 + & 2x_3 + & 20x_4 + & 16x_5 & = & 35{,}000{,}000 \\
 & x_1, & x_2, & x_3, & x_4, & x_5 & = & 0
\end{array}$$

The optimal solution is $x_1 = 0$ tons of steel, $x_2 = 971{,}698$ tons of steel, $x_3 = 28{,}302$ tons of steel, $x_4 = 28{,}302$ tons of coal, $x_5 = 1{,}971{,}698$ tons of coal and $Z = \$2{,}470{,}283$.[41]

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[41] The solution of this example problem is awkward. It would be difficult to install control devices for an arbitrary fraction of a plant's production. Although an integer programming solution would be more realistic, it was found that in the standard linear programming model, divisibility occurs in no more rows than there are binding pollutant requirements (in this example, the nitrogen oxides requirement is not binding). The larger the number of pollution sources, M, in comparison to the number of pollutants, P, the smaller will be the relative importance of the problem of divisibility. In the actual model, the operation of basic oxygen furnaces, blast furnaces, sintering machines, coke ovens, the combustion of coke oven gas, the combustion of fuel oil, and the combustion of natural gas by industry are all treated as individual pollution sources, each with separate production levels and with control method coefficients based on the units in which the corresponding production is measured (i.e., tons of pig iron, tons of sinter, millions of cubic feet of coke oven gas, gallons of fuel oil, etc.). These various activities were combined so as to limit the size of the x vector in the example.

The input-output feedbacks associated with pollution control are now included. In this simple example, there are only four economic sectors: (1) a primary metals sector, (2) a machinery sector, (3) an electric power sector, and (4) a household sector. Assume that the annual purchases of local inputs for pollution control are as follows. Each activity unit of control method x_2 requires $.03 worth of inputs from the machinery sector, $.01 from the electric power sector, and $.02 from the household sector. Each activity unit of control method x_3 requires $.10 worth of inputs from the machinery sector, $.02 from the electric power sector, and $.04 from the household sector. Each activity unit of control method x_5 requires $.20 worth of inputs from the machinery sector, $.20 from the electric power sector, and $.15 from the household sector. The matrix of input requirements is accordingly,

$$H = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & .03 & .10 & 0 & .20 \\ 0 & .01 & .02 & 0 & .20 \\ 0 & .02 & .04 & 0 & .15 \end{bmatrix}.$$

Because no direct inputs are purchased from the primary metals sector, the first row of the H matrix contains only zeros. Because no *incremental* inputs are required for the two existing control methods, columns 1 and 4 contain only zeros. The input requirements for the existing control methods are already incorporated in sector production levels.

The matrix of intersectoral multipliers is determined from a regional interindustry flow model. For this example, it is assumed that,

$$G = \begin{bmatrix} 1.010 & .040 & .005 & .002 \\ .002 & 1.030 & .002 & .001 \\ .100 & .120 & 1.220 & .170 \\ .600 & .870 & .880 & 1.530 \end{bmatrix}.$$

Polluting activities are related to sector levels as follows. For every dollar of sales by the primary metals sector, .0015 tons of steel are produced and .0010 tons of coal are burned at the power plant to provide electricity to the primary metals sector. For every dollar's worth of sales by the machinery sector, by the electric power sector, and by the household sector, .0002, .07, and .0004 tons of coal, respectively, are burned at the power plant. The matrix of coefficients relating pollution source levels to sector sales is,

$$F = \begin{bmatrix} .0015 & 0 & 0 & 0 \\ .0010 & .0002 & .0700 & .0004 \end{bmatrix}.$$

The model with input-output feedbacks is the same as the previous model except that the U matrix is replaced by a $[U - FGH]$ matrix. In the present example, this matrix is,

$$[U - FGH] = \begin{bmatrix} 1 & .999998 & .999994 & 0 & -.000014 \\ 0 & -.001378 & -.003115 & 1 & .979173 \end{bmatrix}.$$

The optimal solution is $x_1 = 0$ tons of steel, $x_2 = 889{,}257$ tons of steel, $x_3 = 110{,}774$ tons of steel, $x_4 = 23{,}357$ tons of coal, $x_5 = 2{,}020{,}290$ tons of coal, and $Z' = \$2{,}540{,}967$. As a consequence of the feedback effect annual steel production rises 31 tons and coal combustion at the power plant increases 43,647 tons a year. The abatement multiplier in this example is \$2,540,967/\$2,470,283, or 1.03.

COMMENT

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Using input-output analysis, Leontief showed that pollution abatement activities generate some pollutants themselves by requiring inputs.[1] For instance, the fans and pumps needed to clean the air use electricity, and the production of this electricity causes additional air pollution. Leontief's illustration raised two empirical questions. Is a significant amount of pollution caused by abatement activities? Do planners have to consider the Leontief effect?

For Kohn's air pollution study of St. Louis, the answer is no. If Kohn's results are supported by other findings, the Leontief effect will be reduced to a theoretically interesting, but empirically unimportant phenomenon. Planners will be able to ignore the effect or dispose of it with a few back-of-the-envelope computations.

Kohn's computations were exhaustive. He included the Leontief effect in a linear programming model of the St. Louis airshed. The model picked the control techniques that achieved a set of emission standards at least cost.[2]

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[1] Wassily Leontief, "Environmental Repercussions and the Economic Structure: An Input-Output Approach," *Review of Economics and Statistics* Vol. LII (August 1970): 262–71.

[2] The model is hard to master. There is much unorthodox terminology, such as an "air pollution control method activity level," which is an amount of some input consumed or output produced that causes pollution. To understand the model, it is sug-

The Leontief effect added only 2.3 per cent to the cost of achieving the standards, a small percentage compared to the other errors and uncertainties that an environmental planner faces. Half of this percentage was achieved without an input-output model, by considering only direct inputs to abatement activities. Kohn showed this by replacing his G matrix with an identity matrix. Kohn assumed that sulfuric acid recovered from power plants and lead smelters was additional production rather than a substitute for existing production. When he tried the alternate assumption that sales were constant and that virgin production was reduced, the Leontief effect was cut from 2.3 per cent to 1.1 per cent.

Kohn's estimates of the Leontief effect may be low, but the bias is probably small. The effects of abatement activities were fed back through only six of the twenty-three sectors in the model, as is reflected by the seventeen zero rows in the H matrix. This means that inputs from the seventeen sectors had no direct or indirect effect on pollution. To the extent that abatement activities used inputs from these sectors and caused additional pollution, the Leontief effect was understated. It is probably true, as Kohn argued, that these sectors are not important, but it would be nice to have enough details in the paper to check his argument. Generally, the paper lacks sufficient detail for the reader to find out what is happening.

Another area where more information is needed is Kohn's treatment of interregional imports. Kohn ignored the effect of pollution control in the St. Louis airshed on pollution levels and pollution control costs in other airsheds, an omission that probably decreased the observed Leontief effect. If St. Louis imports abatement machinery from Cleveland and increases Cleveland's pollution control bill, the additional cost to Cleveland must somehow get back to St. Louis in the form of higher machinery prices. Even if the costs are not passed back, the effect in other regions should be estimated. It seems that Kohn could do this with knowledge of the import sector in Liu's interindustry model.

If Kohn wanted to estimate the size of the Leontief effect, one would think that a reasonable estimate could have been obtained with back-of-the-envelope calculations. By making a crude guess at the direct inputs needed for abatement, estimating the pollution generated, and doubling the figure to account for indirect flows, he would probably have gotten an estimate between 1 per cent and 3 per cent, low enough to forget

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gested that the reader study the numerical illustration in the appendix. or see Robert E. Kohn, "Optimal Air Quality Standards," *Econometrica* Vol. 39 (November 1971): 983–87.

about elaborate modeling and computation. Back-of-the-envelope calculations are very useful for environmental problems. Claims are constantly being made about the importance of this or that environmental effect, and many of these claims can be disposed of by a few calculations with approximate engineering data that are readily available.[3]

The fact that the Leontief effect was small and might have been estimated with simpler computations does not totally erase the importance of Kohn's paper. He did not build the model just to estimate the size of the Leontief effect. He also wanted to advance the art of environmental modeling, which he did. He included pollution abatement activities in an input-output model, demonstrated how linear programming can be used to find the least cost way of achieving ambient standards, and calculated some interesting shadow prices that could be used to achieve the least-cost solution with a set of taxes.

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[3] For an example, it has been claimed that insulating homes does not save energy because energy is required to make the insulation, but simple calculations show otherwise. With typical temperature differentials between the inside and the outside of the home, the insulation can be shown to save more energy in a single year than was required to make it.