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Input-Output Analysis and Air Pollution Control

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Introduction

Some significant research on economics of the environment is taking place in the field of input-output analysis. Leontief has published an important article relating pollution abatement to the economic structure.[1] Isard and his associates are expanding the input-output scope to include ecologic commodities and environmental processes.[2] Miernyk and others have presented papers on the impact of pollution and pollution control on regional economies.[3]

The present paper is, essentially, an empirical sequel of Leontief's. In that article, we are presented with the hypothetical model of a region, in which 30 grams of air pollution is a maximum allowable flow. Because 60 grams are being generated by economic activities, an antipollution

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1. Wassily Leontief, "Environmental Repercussions and the Economic Structure: An Input-Output Approach," *The Review of Economics and Statistics* (August 1970): 262–271.

2. Walter Isard, C. Choguill, J. Kissin, et al., *Ecologic and Economic Analysis for Regional Planning* (New York: The Free Press, 1971).

3. William H. Miernyk, "Environmental Management and Regional Economic Development," *Annual Meetings of the Southern Economic Association and the Southern Regional Science Association*, Miami Beach, Florida, November 6, 1971. J. R. Norsworthy and Azriel A. Teller, "Estimation of the Regional Interindustry Effects of Pollution Control," *Winter Meetings of the Econometric Society*, New Orleans, Louisiana, December 26–29, 1971. David L. Raphael and Ernest E. Enscore, Jr., "The Direct and Indirect Impact of Regional Air Pollution," *Annual Meeting of the Air Pollution Control Association*, Cleveland, Ohio, June 1967.

sector is created to eliminate the excess emissions. The cost of abatement is \$3.00 per gram; thus it might appear that the total cost of pollution control would be \$90.00. This, however, is not the case. The inputs required by the antipollution sector generate increases in the production levels of other sectors which are themselves sources of pollution. When the various multiplier effects are taken into account, it is found that 33.93 grams of air pollution must be eliminated. The total cost of abatement is therefore \$101.80.[4]

Let us define some terms suggested by Leontief's example. The cost of reducing air pollution to some predetermined allowable level, ignoring the economic impact of abatement itself, is Z. The cost of achieving the allowable levels, taking into account the additional flow of pollution resulting from abatement activities, is Z'. For purposes of analysis we then define *the abatement multiplier* as the ratio, Z'/Z. In Leontief's hypothetical model, the abatement multiplier is \$101.80/\$90.00, or 1.131.

The Leontief model assumes a single pollution control process or a fixed combination of processes. In reality, there are many processes for controlling pollution and it is unlikely that they are combined in fixed proportions. The extent to which the abatement multiplier necessitates an expanded level of control and alters the optimal mix of control methods will be investigated in the context of a specific model.

The writer has developed a linear programming model in which maximum allowable flows of five separate pollutants in the St. Louis airshed are specified.[5] A set of air pollution control method activity levels is selected which achieves the allowable flows at the least cost, Z. The abatement multiplier, Z'/Z, for the St. Louis airshed will be calculated, using this same model in conjunction with an input-output study of the St. Louis region.[6]

The value of Z' is determined by augmenting the cost-effectiveness model with appropriate feedbacks. The feedback steps are as follows (the symbols in parentheses are matrix products which will be defined subsequently):

(Hx), the value of economic inputs associated with any set of control method activity levels, x;

4. Wassily Leontief, "Environmental Repercussions," p. 268.

5. Robert E. Kohn, "A Linear Programming Model for Air Pollution Control in the St. Louis Airshed," Ph.D. dissertation, Washington University, 1969.

6. Ben-chieh Liu, *Interindustrial Structure of the St. Louis Region, 1967* (St. Louis: St. Louis Regional Industrial Development Corporation, 1968).

(GHx), the changes in regional production levels necessary to sustain any set of control method activity levels;

($FGHx$), the changes in the levels of polluting activities associated with changes in production levels;

(E^*FGHx), the changes in emission flows (assuming the base year level of control) corresponding to changes in the levels of polluting activities.

The efficient set of control methods, x_0, is now that set which eliminates excess pollution, including the incremental pollution associated (directly and indirectly) with pollution control itself, at the least cost, Z'.

It is presumed that a cost-effectiveness model can be a useful guide for regulatory agencies in selecting an efficient strategy for achieving a predetermined set of air quality goals. In this paper, we investigate the significance of the abatement multiplier for such policy making. This research should provide insight as to how individual cost models and input-output studies can be made more useful for environmental planning. It may also enable us to evaluate the feasibility of incorporating a pollution control sector in the structure of an input-output model.

The Linear Programming Model for Determining Z

In matrix notation, the linear programming model for air pollution control is:

$$\begin{aligned} \text{minimize} \quad & Z = cx; \\ \text{subject to} \quad & Ux = s; \\ & Ex \leq a, \\ & x \geq 0, \end{aligned} \tag{1}$$

where x is an $(N \times 1)$ vector of air pollution control method activity levels and c is a $(1 \times N)$ vector of unit control costs. The vector s is an $(M \times 1)$ vector of pollution source levels, such as the number of tons of coal burned per year in a particular power plant, and the $(M \times N)$ matrix U is a distributive matrix which equates control method activity levels to pollution source levels. The element u_{ij} is 1 when the jth control method is defined for the ith pollution source and zero otherwise. Thus, there are as many 1's in any row of the U matrix as there are control methods defined for the pollution source which corresponds to that row. For the sum of control method activity levels to equal the corresponding pollution source level, it is necessary that both are measured in the same units, that the control method set include M control methods representing the activity levels of the M existing types of control (or noncontrol), and that each control method be uniquely defined for a single pollution source. The element, e_{ij}, of the $(P \times N)$ matrix E is the quantity of pollutant i emitted per activity unit of control method j, and the $(P \times 1)$ vector a is the allowable annual emissions for the P pollutants in the airshed. A simple example which illustrates the model is presented in the appendix to this paper.[7]

Model 1 was implemented as follows. The vector s contains projected levels of 94 polluting sources for the St. Louis airshed in 1975. These levels were projected from observed growth rates or from estimates by industrial representatives. The control method vector x, which includes over 215 alternative control methods in addition to the 94 existing control methods, and the emissions matrix E were developed from available engineering data, with control method costs, c, based on 1968 prices. The allowable annual emission flows, a, were derived from official maximum allowable concentrations for five pollutants in the St. Louis airshed.[8] The annual cost of achieving the air quality goals in 1975 was found to be an estimated $35.3 million over and above the cost of abatement that would be expended given the existing, preregulatory level of control.[9]

The Linear Programming Model for Determining Z'

The increase in polluting activities associated with pollution abatement is Δs. The cost of eliminating excess pollution, including the incremental emissions associated with Δs, is the solution of:

7. The model is described with more detail in Robert E. Kohn, "Optimal Air Quality Standards," *Econometrica* Volume 39 (November 1971): 983–995.

8. The relationship of the annual average concentration of a pollutant to the total annual emissions of that pollutant in the airshed is based on a *proportional model* which is defined on page 15,490 of "Requirements for Preparation, Adoption and Submittal of Implementation Plans," *Federal Register* Volume 36, Number 158 (August 1971). An alternative approach, in which annual emissions are related to ambient air concentrations by means of Gaussian diffusion formulas is used in Robert E. Kohn, "Industrial Location and Air Pollution Abatement," *Journal of Regional Science* Volume 14, Number 1 (April 1974): 55–63.

9. It is the economic impact of incremental costs of abatement that are examined in this paper. For simplicity, the costs of existing control methods are taken as zero and the costs of alternative control methods for any pollution source are incremental costs over and above that of the existing control method. The *total* annual cost of abatement would be in excess of $45 million.

$$\begin{aligned} \text{minimize} \quad & Z' = cx; \\ \text{subject to} \quad & Ux = s + \Delta s; \\ & Ex \leq a, \\ & x \geq 0. \end{aligned} \tag{2}$$

The increase in polluting activities, Δs, is assumed to be a linear function of abatement,[10]

$$\Delta s = FGHx, \tag{3}$$

where F is an $(M \times L)$ matrix, whose element f_{ik} is the change in polluting level i per dollar change in sales of sector k; G is an $(L \times L)$ matrix of intersectoral multipliers, where g_{kK} is the increase in sales of sector k per dollar increase in final demand sales of sector K; and H is an $(L \times N)$ matrix whose element h_{Kj} is the value of inputs from sector K per activity unit of control method j. Substituting for Δs in model 2 and moving $FGHx$ to the left-hand side gives:

$$\begin{aligned} \text{minimize} \quad & Z' = cx; \\ \text{subject to} \quad & (U - FGH)x = s; \\ & Ex \leq a, \\ & x \geq 0. \end{aligned} \tag{4}$$

There may be some incompatibility here in combining an open input-output model, where all production sectors can expand simultaneously, and a cost-effectiveness model in which full employment is implicitly assumed. No attempt will be made here to formulate additional assumptions which might ensure the internal consistency of the model. Most likely such assumptions would allow for an inflow of resources into the airshed. Note that while the costs, cx, are the value of national resources allocated to abatement, it is only the impact on local economic activities, s, that is examined. The effect of pollution control in the St. Louis air-

10. Ayres and Kneese have called attention to the increase in water and soil polluting activities which may be a consequence of air pollution abatement. See R. U. Ayres and A. V. Kneese, "Production, Consumption, and Externalities," *American Economic Review* Volume 59 (June 1969): 282–297. This aspect of air pollution control was examined empirically in Robert E. Kohn, "Joint-Outputs of Land and Water Wastes in a Linear Programming Model for Air Pollution Control," *1970 Social Statistics Section, Proceeding of the American Statistical Association,* Washington, D.C., 1971, pp. 207–214. In the present paper it is the increase in *air* polluting activities as a consequence of the control of air pollution itself which is being examined.

shed on pollution levels and pollution control costs in *other* airsheds is ignored.

The procedures used to calculate the H, G, and F matrices are now described.

The H matrix

The H matrix was implemented to conform with the sector classification in Liu's *Interindustrial Structure of the St. Louis Region, 1967* (see footnote 6). Although Liu distinguished 23 sectors, it was found impractical to allocate each unit control cost among 23 component inputs. Accordingly, six direct input sectors were selected, resulting in an H matrix with 6 nonzero and 17 zero rows. The six sectors are listed in rows 1 through 6 of Table 1. The remaining inputs, which were assumed to have no intersectoral impact, are noted in rows 7 through 10. This table includes selected control methods from the model and the inputs associated with these control methods. The entries in rows 1 through 6 typify elements h_{Kj} of the H matrix and denote the requirements from sector K (rows 1 through 6) per unit of activity of control method j (columns 1 through 8).

The inputs which would be purchased from the chemical, petroleum, and rubber sector include, for example, the increased cost of low sulfur fuel oil (see column 2), dolomite for wet scrubbing stack gases (see column 5), gasoline and diesel fuel for refuse hauling and landfilling equipment (see column 7), etc.

The value of inputs from the machinery sector represents purchases of scrubbers, dust collectors, afterburners, etc. (for convenience all machinery is assigned to the nonelectric machinery sector), while the purchase of automotive control devices and refuse hauling vehicles are attributed to the transportation equipment sector. Although these capital expenditures may be made within the space of five to seven years, the 1975 sector purchases are assumed to be equal to the annual depreciation of the equipment. Since the latter is, in general, based on a longer equipment life than seven years, the purchases from these two sectors may be understated for the year 1975.[11]

A negative purchase from the mining sector represents the value of coal replaced by natural gas (see column 3) while a positive value is the incremental cost of low sulfur coal (see column 4).

The transportation, communication, and utilities sector includes the

11. The assumption that equipment expenditures in any year are equal to depreciation would be more appropriate for a steady state economy.

purchase of natural gas for air pollution control, both as a substitute for coal and a fuel for afterburners. In the case of the dolomite wet scrubbing control method (see column 5), purchases from this sector represent the value of scrubbing water and of electricity to power pumps and fans.

Purchases from the household sector are for labor to maintain and operate control equipment. A negative purchase from the household sector (see column 3) indicates a saving of labor associated with a particular control method.[12]

Miscellaneous unallocated inputs include such items as the equipment and facilities for maintaining control equipment, the nonlabor costs for disposing of nonrecyclable by-products such as dolomite waste (see column 5), the cost of outside soil for landfilling (see column 7), the value of recovered steam in the operation of a carbon monoxide waste heat boiler, etc. While such costs should be allocated to primary sectors, there are other unallocated costs which should not. For example, the saving in household labor when domestic furnaces are converted from coal to natural gas would have no traceable impact on regional economic activity although it is assigned a dollar value.

Although the values of recovered chemicals (e.g., elemental sulfur, ammonium nitrate fertilizer) are included as negative purchases from the chemical, petroleum, and rubber sector, this was not done in the case of sulfuric acid (see row 8) obtained as a result of controlling sulfur dioxide from power generation and lead smelting. It is assumed here that this output represents additional sales of sulfuric acid and has no impact on regional activity other than the inputs required for the operation of the recovery processes.

One of the sectors which should be included as a primary demand sector is local government. It is a limitation of this model that the costs of government regulation and enforcement have been omitted. These could effect the optimal control solution both by altering relative control method costs and through the pollution feedbacks from the expansion of the local government sector.

The opportunity cost of capital (see row 9) represents ten per cent of the total investment in control equipment from the machinery and transportation equipment sectors.[13] For example, the upgraded electrostatic

12. One control method which eliminates local labor is the transfer of a portion of power generating capacity to a mine mouth location outside of the region. So that the results of this paper may be as general as possible, this particular interregional transfer of labor is ignored here.

13. The sensitivity of the model to the opportunity cost of capital is examined in Robert E. Kohn, "Air Quality, the Cost of Capital, and the Multi-Product Production Function," *Southern Economic Journal* Volume 38 (October 1971): 156–160.

TABLE 1

Value of Inputs per Activity Unit for Selected Control Methods

(dollars)

Control Method	*Crankcase and Exhaust Controls for 1970 through 1975 Model Automobiles* (1)	*Maximum Sulfur Content of 1% for Residual Fuel Oil Burned by Industry* (2)	*Conversion of Traveling Grate Stokers with Cyclone Dust Collectors from Coal to Natural Gas by Industrial Firms* (3)	*Maximum Sulfur Content of 2% on Coal Burned by Industry in Traveling Grate Stokers with Electrostatic Precipitators* (4)	*Wet Scrubbing of Stack Gases at Meramec Power Plant with Dolomite* (5)	*Cat-Ox System to Convert Sulfur Dioxide at Portage des Sioux Power Plant to Sulfuric Acid* (6)	*Hauling of Waste to a Sanitary Landfill Instead of Burning It On-Site* (7)	*Upgraded Electrostatic Precipitators for Cement Plant with Current Collection Efficiency of 96.4%* (8)
Control Method Activity Unit →	*One thousand gallons of gasoline burned*	*One thousand gallons of residual fuel oil burned*	*One ton of coal burned*	*One ton of coal burned*	*One ton of coal burned*	*One ton of coal burned*	*One ton of waste disposed*	*One barrel of cement produced*
(1) Value of direct inputs from chemical, petroleum, and rubber sector	0	5.00	0	0	.22	0	.30	0
(2) Value of direct inputs from nonelectric machinery sector	0	0	0	0	.19	.58	0	.04
(3) Value of direct inputs from transportation equipment sector	9.23	0	0	0	0	0	1.50	0

(4) Value of direct inputs from mining sector	0	0	−5.27	2.50	0	0	0	0
(5) Value of direct inputs from transportation, communication, and utilities sector	0	0	11.27	0	.20	.36	0	*n**
(6) Value of direct inputs from household sector	3.70	0	−1.57	0	.15	.24	7.20	.01
(7) Miscellaneous unallocated inputs	.91	0	−.06	0	.05	.27	1.16	.01
(8) Sulfuric acid produced from sulfur dioxide	0	0	0	0	0	−1.34	0	0
(9) Opportunity cost of capital	4.62	0	0	0	.39	1.16	1.00	.05
(10) Scarcity premium for natural gas	0	0	3.80	0	0	0	0	0
Total Control Method Unit Cost	18.46	5.00	8.17	2.50	1.20	1.27	11.16	.11

* *n* less than one half cent.

precipitator for a specific category of cement plant (see column 8) requires an incremental capital investment of $.50 per barrel of cement produced. It is assumed here that capital investments in control equipment are additional expenditures in the region and do not replace other planned investments. Hence, there is no feedback on polluting levels in the airshed.[14]

Another economic cost which is assumed to have no current impact on regional activity is the scarcity premium for natural gas (see row 10). This represents the excess of the social value of natural gas used for pollution control over its regulated market value.[15] The costs in the final row of Table 1 are unit control costs from the vector c. Each is the sum of input values in that column.

The G matrix

The G matrix is taken directly from Liu's input-output study and contains intersectoral multipliers for the St. Louis region. A portion of this matrix is reproduced in Table 2. Each entry shows, per dollar of direct sales of inputs for pollution control by the sector at the top, the total dollar value of production directly and indirectly required from the sector on the left. These multipliers are based on a model in which the household and local government sectors are endogenous.

It is assumed here that the technology, trading patterns, and relative prices for 1967 are applicable to 1975, although Miernyk notes that an input-output structure with fixed coefficients should be projected no more than two or three years.[16]

The F matrix

The X vector in Leontief's model represents sector activity variables and his emission factors, a_{gi}, relate directly to sector levels.[17] However, it is

14. In their regional impact model, Norsworthy and Teller, "Regional Interindustry Effects of Pollution Control," p. 18, use the opportunity cost of capital as a proxy for purchases from the machinery and construction sectors. They treat depreciation as a cash flow to households and imports. In the present study, only the impact of actual production activities are considered.

15. The scarcity premium for natural gas is discussed in Robert E. Kohn, "Application of Linear Programming to a Controversy on Air Pollution Control," *Management Science* Volume 17 (June 1971): 609–621.

16. William H. Miernyk, *The Elements of Input-Output Analysis* (New York: Random House, 1965), p. 33.

17. Leontief, "Environmental Repercussions," p. 271.

convenient in air pollution control models to identify polluting activities, *s*, across conventional sector classifications. Many of the 94 separate polluting activities defined in this model occur in each of the industrial sectors (e.g., the combustion of coal in various types of stokers, evaporation of industrial solvents, combustion of diesel fuel in trucks, disposal of refuse by open burning, etc.). To define each of these pollution sources according to sector as well as type would multiply the control method set enormously. In order then to relate polluting levels, as defined in the present model, to input-output multipliers based on a conventional economic sector classification, a conversion matrix is required. The *F* matrix fills this need.

The coefficients of the *F* matrix indicate changes in polluting levels associated with changes in sector sales. They are illustrated in table 3 for selected pollution sources.[18] In the case of gasoline burned in motor vehicles (see row 1), it was assumed that the ratio of gasoline consumption in 1967 to the value of retail trade services in that same year, which was 643.52 thousand gallons per million dollars of sector activity, is a constant.[19] The production of cement, primary steel, grain handling, and sulfuric acid were assumed to be proportional to the sales of the respective standard industrial code classification sector, with the constant of proportionality based on 1967 levels.[20]

The combustion of coal in industrial furnaces was based on the sales of thirteen industry sectors. It was estimated, for example, that the food, tobacco, and kindred products sector used 96.3 tons of coal per million dollars of sales in 1967.[21] It was projected that in 1975, given the same level of pollution control as existed in 1963, which was the base-year in

18. For convenience, the coefficients in Table 3 are related to *millions* of dollars of sector activity.

19. Gasoline consumption in the St. Louis region in 1967 was an estimated 857,143 gallons (Kohn, "A Linear Programming Model," p. 553) and retail trade services in that year totaled $1,350,862,000 (Liu, *Interindustrial Structure*, Table IV–1). The reader is cautioned that the *F* matrix, like the *G* matrix, is based on the assumption that the technological relationships and relative prices that prevailed in 1967 are applicable for 1975.

20. Four categories of cement plants are included in the model. It is assumed that the older plants (see, for example, column 8 in table 1) are at capacity, so that any increases in cement production will take place in newer plants equipped with 99.4% efficient electrostatic precipitators. To this limited extent, the present study incorporates a normal advance in abatement technology.

21. Extrapolated from data in *1963 Census of Manufactures, Volume I, Summary and Statistics* (Washington, D.C.: U.S. Department of Commerce, 1966), pp. 45, 7–92 and in *1967 Census of Manufactures, Missouri* (Washington, D.C.: U.S. Department of Commerce, 1970), pp. 26–14, 26–15, 26–16.

TABLE 2

Selected Elements of the Matrix of Intersectoral Multipliers for the St. Louis Region

	Chemicals, Petroleum, and Rubber Products (5)	*Machinery (except electrical)* (10)	*Transportation Equipment* (12)	*Mining* (15)	*Transportation, Communication, and Utilities* (17)	*Household* (22)
(1) Food, tobacco, and kindred products	.0243	.0513	.0216	.0544	.0525	.0892
(2) Textiles and apparel	.0047	.0101	.0043	.0108	.0102	.0173
(3) Lumber and furniture	.0011	.0026	.0010	.0024	.0024	.0037
(4) Paper and printing	.0135	.0158	.0079	.0183	.0207	.0233
(5) Chemicals, petroleum, and rubber products	1.0613	.0126	.0063	.0137	.0119	.0201
(6) Leather products	.0007	.0017	.0007	.0017	.0016	.0027
(7) Stone, clay, and glass	.0138	.0038	.0017	.0040	.0040	.0063
(8) Primary metals	.0019	.0346	.0166	.0071	.0046	.0022
(9) Fabricated metals	.0066	.0271	.0057	.0163	.0050	.0060
(10) Machinery (except electrical)	.0008	1.0255	.0062	.0067	.0018	.0010
(11) Electrical machinery	.0014	.0026	.0022	.0017	.0036	.0020
(12) Transportation equipment	.0048	.0122	1.0165	.0114	.0121	.0181
(13) Miscellaneous manufacturing	.0018	.0037	.0083	.0025	.0029	.0034
(14) Agriculture	.0013	.0028	.0012	.0030	.0029	.0049

(15) Mining	.0028	.0014	.0008	1.0262	.0029	.0014
(16) Construction	.0057	.0112	.0048	.0128	.0189	.0166
(17) Transportation, communication, and utilities	.0887	.1168	.0561	.2865	1.2178	.1676
(18) Wholesale trade services	.0118	.0306	.0094	.0213	.0219	.0234
(19) Retail trade service	.0571	.1419	.0561	.1332	.1309	.2082
(20) Finance, insurance, and real estate	.0680	.1429	.0613	.1807	.1619	.2245
(21) Business, personal, and other services	.0540	.1153	.0484	.1285	.1309	.1833
(22) Household	.3938	.8674	.3665	.9249	.8756	1.5313
(23) Local government	.0240	.0491	.0199	.0535	.0672	.0745

Source: B. C. Liu, *Interindustrial Structure of the St. Louis Region, 1967* (St. Louis: St. Louis Regional Development Corporation, 1968), Table V–1.

TABLE 3

Detail of the Matrix for Relating Increased Polluting Levels to an Increase in Sector Sales of One Million Dollars

	Food, Tobacco, and Kindred Products (1)	*Textiles and Apparel* (2)	*Lumber and Furniture* (3)	*Paper and Printing* (4)	*Chemicals, Petroleum, and Rubber Products* (5)	*Leather Products* (6)	*Stone, Clay, and Glass* (7)	*Primary Metals* (8)	*Fabricated Metals* (9)	*Machinery (except electrical)* (10)
(1) Thousands of gallons of gasoline burned in automobiles	0	0	0	0	0	0	0	0	0	0
(2) Tons of coal burned by industry in traveling grate stokers with cyclone controls	6.26	1.24	3.75	22.83	20.59	6.59	53.16	19.55	2.26	4.45
(3) Tons of coal burned by industry in pulverized coal units with 90% efficient electrostatic precipitators	37.56	7.42	22.38	136.35	123.02	39.34	317.57	116.79	13.48	26.55
(4) Tons of coal burned in the Meramec Power Plant	7.93	2.55	4.95	10.60	20.01	6.06	55.06	38.58	9.18	4.44
(5) Tons of coal burned in the Portage des Sioux Power Plant	32.59	10.48	20.33	43.71	82.23	24.91	226.31	158.54	37.71	18.26
(6) Tons of waste disposed of by on-site open burning	13.24	15.42	60.11	10.44	39.56	43.57	181.31	23.38	19.38	26.93
(7) Barrels of cement produced in cement plant with 99.4% efficient electrostatic precipitators	0	0	0	0	0	0	43210.	0	0	0
(8) Tons of primary steel produced in basic oxygen furnaces	0	0	0	0	0	0	0	1470.6	0	0
(9) Tons of grain handled and processed in elevators	1869.2	0	0	0	0	0	0	0	0	0
(10) Tons of sulfuric acid produced by the contact process	0	0	0	0	701.55	0	0	0	0	0
(11) Tons of dry cleaning solvents used	0	0	0	0	0	0	0	0	0	0

(continued)

the pollution model, approximately 6.5% of the industrial coal burned in the St. Louis region would be burned in traveling grate stokers with cyclone controls. Accordingly, for every million dollars in sales by the food, tobacco, and kindred products sector, (96.3) × (.065), or 6.26 tons of coal would be burned in this furnace category (see row 2, column 1). Be-

TABLE 3 (*concluded*)

Electrical Machinery (11)	*Transportation Equipment* (12)	*Miscellaneous Manufacturing* (13)	*Agriculture* (14)	*Mining* (15)	*Construction* (16)	*Transportation, Communication, and Utilities* (17)	*Wholesale Trade Services* (18)	*Retail Trade Services* (19)	*Finance, Insurance, and Real Estate* (20)	*Business, Personal, and Other Services* (21)	*Household* (22)	*Local Government* (23)
0	0	0	0	0	0	0	0	643.52	0	0	0	0
2.78	3.37	3.35	0	0	0	0	0	0	0	0	0	0
16.59	20.10	19.99	0	0	0	0	0	0	0	0	0	0
10.46	6.23	9.19	3.91	17.46	3.66	2600.[a]	8.03	9.22	13.42	16.06	12.12	7.18
42.98	25.60	37.77	16.08	71.74	15.03	10710.[a]	33.01	37.89	55.16	66.01	49.83	29.50
26.93	11.68	2.40	0	38.05	5.51	8.79	12.19	18.92	5.63	17.32	24.97	31.60
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	3.29	0	0	0	0

[a] Tons of coal burned per million dollars of electric power sold.

cause the combustion of industrial coal in pulverized coal furnaces equipped with 90% efficient electrostatic precipitators represents 39.0% of the projected coal combustion in 1975, the corresponding coefficient for this polluting activity is larger (row 3, column 1).

It could have been assumed that coal combustion in individual power plants is proportional to sales of the transportation, communications, and utilities sector. However, this would mean that a million dollars in sales of natural gas for air pollution control would have the same impact on power plants as would the sale of a million dollars of electricity. To avoid a serious distortion in the model, it was assumed that the sale of natural gas had no direct effect on power plant activity. This required a separate accounting of natural gas and electricity inputs for air pollution control. The coefficient relating coal combustion at the Meramec Power Plant to a million dollars of electricity sales (row 4, column 17) was obtained as follows. It was assumed that a million dollars in sales to industrial users represents 93,620,000 kilowatt hours of electricity.[22] The Meramec Power Plant, which burns approximately .000427 tons of coal per kilowatt hour produced will supply an estimated 6.5% of the area's power requirements in 1975. Accordingly, the appropriate element of the F matrix is (93,620,-000) × (.000427) × (.065), or approximately 2,600 tons of coal per million dollars of sales of electricity.

The sale of natural gas as well as electricity would affect power plant activity via the impact on other economic sectors. For example, it was estimated that 381,950 kilowatt hours of electricity are required by the paper and printing sector per million dollars of sales.[23] The f_{ik} coefficient of the Meramec Power Plant for this industrial sector is therefore (381,-950) × (.000427) × (.065), or 10.6 tons of coal per million dollars in sales by the paper and printing sector (see row 4, column 4).

It was estimated that for each million dollars of sales by the primary metals sector, there would be 96.2 tons of nonrecycled solid waste generated.[24] Assuming, in the absence of regulatory activity, that 24.3% of solid waste in the St. Louis region is disposed of by on-site open burning,[25] it was estimated that (96.2) × (.243), or 23.38 tons of waste would be burned on industry property per million dollars of metal sales (see row 6, column 8).

22. The average price of electricity sold to industrial users by Union Electric Co. in 1967 was $.010682 per kilowatt hour. See *1967 Annual Report* (St. Louis: Union Electric Co., 1967), p. 26.

23. A breakdown of power shipments to St. Louis industrial sectors was provided by Union Electric Co. and Illinois Power Co. The breakdown of power shipments to non-industrial sectors was estimated from data in Liu, *Interindustrial Structure,* table IV–1.

24. Waste production data are based on a study by the Institute of Industrial Research, University of Louisville, *Louisville, Ky.—Ind. Metropolitan Region Solid Waste Disposal Study, Volume I, Jefferson County, Kentucky* (Cincinnati, Ohio: U.S. Department of Health, Education and Welfare, 1970), pp. 6, 7, 25, 95, 96.

25. Relative polluting activity levels in the St. Louis airshed in 1975 are taken from Kohn, "A Linear Programming Model."

The effect of the F matrix is to relate directly the level of a polluting activity to the production level of either a single economic sector, or in the case of coal and refuse burning, to a linear combination of sector levels.

The FGH matrix product

The ijth element of the FGH matrix product represents the change in source level i per unit of control method j activity. This element has the form,

$$\sum_{k=1}^{L} \sum_{K=1}^{L} f_{ik} g_{kK} h_{Kj}.$$

For example, when one ton of waste, customarily burned on-site, is hauled away for landfill disposal (see table 1, column 7), the increased combustion of gasoline in automobiles is an estimated (643.52) (.0571 × .30 + .0561 × 1.50 + .2082 × 7.20)(10^{-6}), or approximately .001 thousand gallons (see table 2, row 19 and table 3, row 1).[26]

It should be noted that there are other feedbacks of abatement activity on polluting levels which are not included here. If the private costs of control are added to the selling prices of pollution-related intermediate and final goods and services, there may be substitutions which reduce the levels of polluting activities.[27] Furthermore, the abatement of pollution may result in technical efficiencies which reduce the level of polluting activities.[28]

26. The previously noted exception for the transportation, communication, and utilities sector can be formally stated. For elements, $\Sigma_k \Sigma_K f_{ik} g_{kK} h_{Kj}$, in which both subscripts k and K denote the transportation, communication, and utilities sector, the coefficient h_{Kj} is the value of the electricity input only. When subscript k refers to any of the other economic sectors, h_{Kj} represents the combined value of natural gas, water, and electric power inputs.

27. This type of feedback is programmed into the model in Robert E. Kohn, "Price Elasticities of Demand and Air Pollution Control," *Review of Economics and Statistics* Volume 54 (November 1972): 392–400.

28. Raphael and Enscore, "Impact of Regional Air Pollution," have modified an input-output model for Clinton County, Pennsylvania so that the technical coefficients describing the production structure are altered by air pollution levels. In addition, certain sector levels, e.g., the production of cleaning services are a function of pollutant concentrations. Because the technological and human effects of air pollution are not as well known as the costs of abatement, cost-effectiveness models for air pollution control are more satisfactorily implemented with empirical data than are benefit-cost models. However, when the costs of abatement are thoroughly investigated it becomes apparent that the damage effects of air pollution cannot be ignored, even in a cost effectiveness model.

Results: The Abatement Multiplier

The abatement multiplier is a measure of the increase in the cost of pollution control caused by input-output feedbacks of the control technology on the vector of polluting activities. It is defined as the ratio of Z' to Z. If we let x_0 represent the optimal control method solution of the feedback model, (4), the minimized cost of pollution abatement, Z', is the product cx_0. This cost was found to be $36.1 million, which compares to a cost of $35.3 million for the original model (1) in which the feedbacks were ignored. The abatement multiplier is therefore equal to 1.023.

The factors which determine the size of the abatement multiplier will be investigated here. It will be useful to examine the following: x_0, the optimal set of control methods; Hx_0, the total value of direct inputs for abatement; GHx_0, the increase in economic sector production levels; $FGHx_0$, the changes in polluting source levels; and E^*FGHx_0, the additional emissions which must be eliminated.[29]

Optimal control method activity levels, x_0

Selected activity levels of the x_0 vector are listed in table 4. These are compared to corresponding activity levels from the solution of the original model. The fact that control method activity levels do not increase in the same proportion demonstrates that there is a shift in abatement technology. Because the efficient control method set is altered as the level of control is increased, it is clear that the abatement multiplier as defined in this paper differs from conventional input-output multipliers, which are based on fixed technological relationships.

The major change in the control method solution is a 15 per cent overall increase in the quantity of natural gas required for pollution control. For traveling grate stokers equipped with cyclone collectors, there is a sharp increase in the substitution of natural gas for coal (see table 4). Another control method, representing the conversion of a different category of stoker from coal to natural gas, entered the basis in the second solution.

Direct inputs for pollution control, Hx_0

Of the $36.1 million in annual costs of pollution control, only $24.1 million are assumed to have an input-output feedback. This is the sum of the

29. The matrix E^* will be defined subsequently.

TABLE 4

Optimal Activity Levels of Selected Control Methods in the Original Model and the Feedback Model and Total Cost of Abatement

Control Method	*Control Activity Level in the Original Model*	*Control Activity Level in the Feedback Model*	*Ratio of Control Levels (feedback model to the original model)*
Exhaust control device for 1970 to 1975 model automobiles	545,638,000 gallons of gasoline combustion controlled	548,319,000 gallons of gasoline controlled	1.005
Crankcase evaporation control device for 1970 to 1975 model automobiles	25,885,000 gallons of gasoline combustion controlled	40,249,000 gallons of gasoline controlled	1.555
Upgraded electrostatic precipitators for industrial pulverized coal furnaces	444,000 tons of coal combustion controlled	444,615 tons of coal combustion controlled	1.001
Conversion of traveling grate stokers with cyclone controls from coal to natural gas	106,030 tons of coal combustion controlled	173,185 tons of coal combustion controlled	1.633
Desulfurization process for the Meramec Power Plant	730,000 tons of coal combustion controlled	740,330 tons of coal combustion controlled	1.014
Conversion of burning dumps to sanitary landfill	455,000 tons of refuse burning controlled	455,516 tons of refuse burning controlled	1.001
High energy wet scrubber for blast furnaces	1,417,500 tons of iron production controlled	1,417,846 tons of iron production controlled	1.000
Annual cost in 1975 for all air pollution control method activity levels combined	$35.3 million	$36.1 million	1.023

nonzero elements of the matrix product Hx_0, which are listed in the upper part of table 5. The larger the portion of Z' which reflects direct pur-

TABLE 5

Value of Direct Inputs for an Efficient Set of Air Pollution Control Methods in the St. Louis Airshed in 1975

(millions of dollars)

Inputs	*Value of Inputs*	
Assigned to an Input-Output Sector (Hx_0)		
Chemicals, petroleum, and rubber products sector	.4	
Machinery sector	6.7	
Transportation equipment sector	8.7	
Mining sector	−13.0	
Transportation, communication, and utilities sector		
Electric power only	3.2	
Natural gas, etc.	13.3	
Household sector	4.8	
Subtotal		24.1
Not Assigned to an Input-Output Sector		
Miscellaneous unallocated inputs	1.6	
Credit for by-product sulfuric acid produced from sulfur dioxide	−11.9	
Opportunity cost of capital	19.4	
Scarcity premium for natural gas	2.9	
Subtotal		12.0
Total value of inputs		36.1

chases in the region the greater will be the abatement multiplier. In a more elaborate model all of the "miscellaneous unallocated inputs" would be assigned to appropriate input-output sectors and the abatement multiplier would be larger.

If the recovered by-product sulfuric acid were to diminish current production of sulfuric acid in the chemical sector, this would reduce the sum of elements of the product Hx_0, and the abatement multiplier accordingly. A sensitivity test with the model indicated that if the \$11.9 million worth of recovered sulfuric acid were to replace an equal valued 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

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-

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	[a]
(10) Rock and gravel crushed, screened, conveyed, and handled	4,000,000 tons of rock	1,225 tons of rock	[a]

[a] Less than .05%.

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

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

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

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-

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]

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]

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 eflect 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

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.

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.