Clean Air with Economic Growth: Optimization Modeling

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ABSTRACT / Conflicts between the goals of having clean air and economic development are widespread. This paper discusses the conceptual and mathematical development of a linear programming optimization model and an interative solution procedure to determine optimal economic development strategies to promote employment subject to various contexts which limit air pollution carrying capacity. Three cases are formulated: (1) maximizing employment subject to ambient concentration constraints, (2) maximizing employment subject to emissions constraints, and (3) minimizing emissions subject to employment constraints. Empirical relationships using Census and pollutant inventory data describe a conceptual urban system, so that indirect and induced impacts of development strategies are also included. The modeling incorporates both point and nonpoint sources, and is shown to be adaptable for nonreactive emissions.

Since the latter part of the 1960's, considerable attention has been devoted to the use of optimization models in problems of environmental quality analysis. Most frequently, optimization models have been used to determine both site-specific and regional least cost measures of meeting both emission and ambient standards; for example Kohn (1970 and 1978) and Gorr and others (1971). This paper discusses a somewhat different use of optimization modeling in environmental analysis, a linear programming approach to help determine optimal urban economic development strategies under air pollution constraints.

In spite of substantial programs and expenditures, unacceptable levels of ambient air quality remain over large portions of the United States (U.S. Council on Environmental Quality 1978) and other western countries. Moreover, continued economic and population growth in medium-sized urban areas threaten to exceed the carrying capacity of airsheds. Hence there has been increasing concern as to how to allow for continued economic development while maintaining desired levels of ambient air quality consistent with protecting human health and aesthetics. This concern is being expressed in the United States in terms of various Federal regulatory efforts such as air quality maintenance, the prevention of significant deterioration, and the Air Quality Technical Assistance Demonstration Program (Kurtzweg and Nelson 1980, U.S. Environmental Protection Agency 1980) which seek to explore new strategies for economic development in nonattainment areas.

However there have been very few attempts to expand earlier uses of optimization modeling towards the development of comprehensive interdisciplinary conceptual and mathematical models of economic development and environmental quality in a spatial framework with the objective of determining optimal economic development strategies. Such initiatives have come primarily from individuals in other western countries. Muller (1973) discussed a linear programming model which utilized input–output relationships and sought to maximize regional income under constraints of ambient air quality in the Netherlands. Werczberger (1974) presented a linear programming model for application in Israel to maximize the profit from land development subject to various constraints of air, water, and solid waste. More recently, Guldmann and Shefer (1980) have investigated least cost locational strategies for industrial development in accordance with emission density management in the Haifa metropolitan area.

While the economic objectives and economic constraints have been formulated rather well in these prior models, they have other severe conceptual limitations in general. Substantive geographic aspects of air quality, such as the spatial allocation of continued area growth and the inclusion of important area sources, are generally overlooked. Moreover, the economic-environmental system is not explicitly defined with respect to what is exogenous versus what is endogenous to the system. Perhaps this is because important indirect and induced pollutant sources resulting from commerce and population growth are generally omitted from the system. Finally, temporal considerations in optimization modeling have been rather cursory; annual average constraints have always been considered, whereas experience has generally shown that other, shorter time periods are limiting with respect to area carrying ca-

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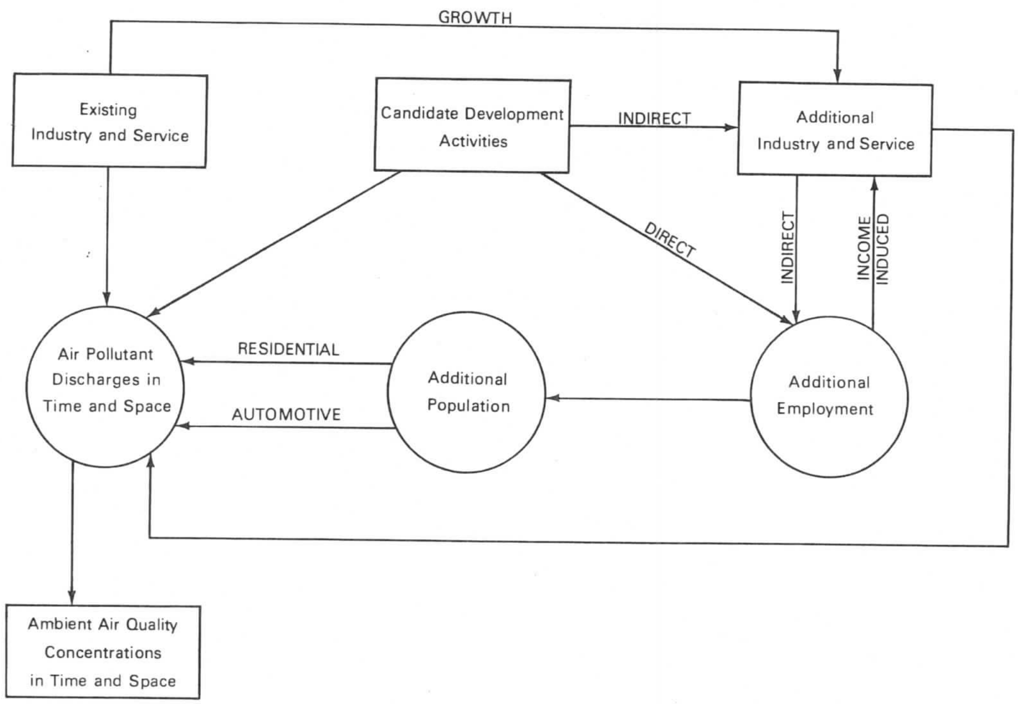

Figure 1. Conceptual interactions of urban growth and air quality impacts.

pacity. In this paper, the conceptual development of a linear programming optimization model is sought to remedy these difficulties.

The Conceptual Urban System and Optimization Alternatives

Before proceeding to the development of optimization models in a quantitative manner, it is important to conceptualize and define the system we seek to model. Figure 1 contains a conceptual diagram of the urban and growth characteristics which affect both employment and air quality.

Assume that at some time there exist given vectors of industrial and service economic dollar output and employment, a given level of population, and a given state of ambient air quality. We then wish to determine an optimal combination of candidate economic development activities which meets certain employment and air quality objectives. Ultimately, implementation of the economic development strategy by some combination of economic incentives and zoning is desirable. At the same time, in fairness, it is necessary to allow for some resonable growth factor of existing economic activities. The activities to be developed will have direct and indirect impact in terms of both added employment and air pollutant emissions. In turn, the added employment will produce income and income-induced economic activities, primarily in the form of increased demand for services. The additional employment opportunities tend to increase population through migration, and residential and automotive emissions are therefore increased as well. Clearly all of the increased emissions will tend to increase ambient concentrations at different receptor locations.

Given the complexity of the increasing human and natural systems interactions at the urban scale, the optimization problem becomes a matter of finding an objective function of economic development activities which will serve as the development strategy and which, together with the indirect and induced impacts noted above, will not violate a set of air pollution constraints. There are two basic choices which the objective function can offer in order to resolve the economic growth and development versus clean air conflict. Frequently the prevailing value judgment in most urban areas will be to maximize some economic objective, such as wages or employment, while assuring at least a given level of ambient air quality. Hence the air qualiy constraints would be utilized such that the sum of air quality deterioration from the direct vector of economic activities added to the air quality deterioration from indirect and induced economic and population impacts would not exceed desired concentrations at various receptor locations for the respective air pollutants of concern. Alternately, some communtities could conceivably desire to minimize pollutant emissions (an objective function to minimize receptor concentrations would normally be unduly complex) subject to generating a certain level of employment or income. These two fundamental choices are developed in a later section of the paper.

Basic Definitions and Formulations

Before proceeding with the formulation of the linear program models, it is useful to provide a quantitative development of some important model elements in accordance with the conceptual urban system described above. The key variables are developed as empirical functions of production output at the end of some planning period (the independent variables) and they utilize data which either are readily available or can be easily derived from available data such as Census materials and pollutant inventories. It should be emphasized that as underlying structural relationships and lifestyles change over time, such as from one planning period to the next, the magnitude of the empirical coefficients will change also.

Employment and Wage Generation

The employment elasticity coefficient has been defined as follows:

$$\text{Employment elasticity coefficient} = \left(\frac{E_n{}^2 - E_n{}^1}{E_n{}^1}\right) \Big/ \left(\frac{K^2 X_n{}^2 - X_n{}^1}{X_n{}^1}\right)$$

$$= \left(\frac{X_n{}^1}{E_n{}^1}\right)\left(\frac{\Delta E_n}{\Delta X_n}\right) \qquad (1)$$

where $E_n{}^2$ is the direct employment at time 2 for some economic activity n, $E_n{}^1$ is the direct employment at time 1,$X_n{}^2$ is the output at time 2 for some economic activity n (dollars), $X_n{}^1$ is the output at time 1 (dollars), and K^2 is the dollar deflator to convert output at time 2 to time 1 dollars.

Although the reader may obtain a more detailed discussion elsewhere, (Muschett 1978, 1981) a few salient points relative to the employment elasticity coefficient bear repeating here. The employment elasticity coefficient is the ratio of the fractional change in direct employment compared to the fractional change in (real) output for a given economic activity for all establishments over some time period. From readily available Census information, the employment elasticity coefficient is intended to provide a measure of employment generated by the expansion of a given activity. It should be noted that the employment elasticity coefficient approach must be exercised more carefully for declining economic activities; the coefficient must be calculated for another area and applied to the area of interest for the given activity. The above definition of the employment elasticity coefficient may be arranged for any given activity to yield:

$$E_n{}^2 = E_n{}^1\left[\underline{EE}_n\left(\frac{X_n{}^2}{X_n{}^1} - 1\right) + 1\right]$$

$$= E_n{}^1\underline{EE}_n\frac{X_n{}^2}{X_n{}^1} - E_n{}^1\underline{EE}_n + E_n{}^1 \qquad (2)$$

where $EE_n$is the employment elasticity coefficient for activity n and the other terms are as previously defined.

Thus in equation (2), employment from any given economic activity at the end of some planning period is defined as a linear function of the output at the end of the period. However, over time from Census period to Census period, the employment elasticity coefficients can be recomputed to account for actual aggregated, non-linear changes in the factors of production ($\Delta E/\Delta X$)for establishments in the area. Finally, for a given economic activity the income generated may be defined by multiplying the employment times the average wage:

$$I_n = w_n{}^2 E_n{}^2$$

$$= w_n{}^2 E_n{}^2\underline{EE}_n\frac{X_n{}^2}{X_n{}^1} - w_n{}^2E_n{}^1\underline{EE}_n + w_n{}^2E_n{}^1 \qquad (3)$$

where I_n is the income from nth economic activity (dollars), w_n is the average wage (dollars per worker), and other variables are as previously defined.

Pollutant Emissions

As noted during the conceptualization of the urban system, production output has indirect effects upon pollutant generation resulting from increases in employment and population. In this section, relationships among population, employment, and output are defined. Then relationships between population and automotive emissions and population and residential combustion emissions are defined. Ultimately pollutant generation from these indirect and induced sources are defined as a function of production outputs.

Unless an adjustment is needed for outmigration, population is equal to:

$$\begin{aligned} P^2 &= P^1 + \left(\frac{\Delta P}{\Delta E^*}\right)(\Delta E^*) \\ &= P^1 + \left(\frac{\Delta P}{\Delta E^*}\right)(\Delta E)(S) \\ &= P^1 + qs\left(\sum_n E_n{}^2 - E_n{}^1\right) \\ &= P^1 + qs\left(\sum_n E_n{}^1 \underline{EE}_n \frac{X_n{}^2}{X_n{}^1} - E_n{}^1 \underline{EE}_n\right) \end{aligned} \tag{4}$$

where P^2 is the population at the end of the planning period, P^1 is the population at the beginning of the planning period, E^* is the total employment from all economic activities, E_n is the industrial employment in nth activity, q is the ratio of change of population to change in total employment, and s is the type II employment multiplier. It should be noted that q may be computed from Census sources, P^1 is directly available from Census sources, and s is generally available in the economic literature. Thus P^2 is presented as a linear function of the industrial output vector.

Now it remains to define the pollutant emissions as related to population. For purposes of this paper, other transportation emission sources may be neglected in comparison to the automotive emissions. The total annual automotive emissions may be defined:

$$\begin{aligned} A^2 &= tP^2vh \\ &= tvh\left[P^1 + qs\left(\sum_n E_n{}^1 \underline{EE}_n \frac{X_n{}^2}{X_n{}^1} - E_n{}^1 \underline{EE}_n\right)\right] \end{aligned} \tag{5}$$

where A^2 is the annual automotive emission at time 2 (gm), t is the automobiles owned per capita, v is the annual average vehicle miles per automobile, and h is the average emissions per vehicle mile (gm/mi).

The annual residential combustion emissions may be defined in an analogous manner:

$$\begin{aligned} R^2 &= zP^2 \\ &= z\left[P^1 + qs\left(\sum_n E_n{}^2 \underline{EE}_n \frac{X_n{}^2}{X_n{}^1} - E_n{}^1 \underline{EE}_n\right)\right] \end{aligned} \tag{6}$$

where R^2 is the annual residential combustion emissions at time 2 (gm) and z is the combustion emissions per capita.

Finally, we wish to estimate the annual combustion emissions from the commercial (service) sector at the end of the planning period. An empirical relation ($\Delta S/\Delta X^*$) between changes in numbers of service establishments in relation to changes in total industrial output is obtained from Census data and assumed for the planning period:

$$C^2 = C^1 + \left(\frac{C^1}{S^1}\right)\left(\frac{\Delta S}{\Delta X^*}\right)(\Delta X^*) \tag{7}$$

where C^2 is the annual service sector combustion emissions at time 2 (gm), C^1 is the annual service sector combustion emissions at time 1, S^1 is the number of service establishments at the beginning of the planning period, $\Delta S/\Delta X^*$ is the rate of increase in service establishments with respect to rate of increase in total (direct plus indirect) industrial output, and X^* is the change in total industrial output during the planning period (dollars).

All of the above definitions are required later to determine indirect and induced pollutant emission impact as part of an iterative solution of the linear programming model.

Spatial Aggregation of Pollutant Sources and Air Quality Modeling

In the optimization model, ambient pollutant concentration constraints will define an allowable incremental increase in ambient air quality concentrations at receptor points from various sources. Air quality diffusion models have gained widespread acceptance to estimate air quality impacts; the ambient air quality concentration is equal to a constant, the dilution factor (or transfer coefficient) times the source emission rate. Prior to using the appropriate air quality diffusion model to estimate a dilution factor, however, the sources must be defined as point, area, or line source pollutants. Both residences and service activities tend to be dispersed spatially throughout urban areas, including the Central Business District (CBD), suburban shopping centers, commercial strips, and various socio-economic neighborhoods. Because of this disaggregation and the fact that individual sources are relatively small in comparison to industrial sources, it is convenient to treat residential emissions, automotive emissions, and service sector emissions as area sources; an area source emission model can be used in order to calculate an areawide ambient air pollutant concentration as part of a constraint upon air quality (Gifford and Hanna 1973):

$$C_A = d_A Q \qquad (8)$$

$$= \frac{K_p}{Au} Q \qquad (9)$$

where C_A is the ambient concentration from area sources (gm/m^3), d_A is the area source dilution factor (m^3/sec), Q is the area source emission rate (gm/sec), K_p is the constant which varies with pollutant (dimensionless), A is the urban area (m^2), and u is the annual average wind speed (m/sec).

Since u, K_p, and A are constants, concentration is a linear function of the emission rate. From (5), (6), and (7) we find the areawide emissions from the automotive, residential, and service sector combustion sources, respectively, and insert into (9) in order to estimate ambient areawide concentrations resulting from induced population and service growth.

Significant industrial sources require better spatial resolution as industrial point sources. The industrial point sources are then input into an annual average Gaussian diffusion model for point sources in order to estimate air quality impacts at the receptor points. For a detailed review of air quality models, the reader is referred to Johnson and others (1976) and Muschett in press.

Linear Program Model Formulation

Contexts and Assumptions

In this section the preceding definitions will be incorporated towards the ultimate objective of determining an optimal area economic development strategy consistent with air pollutant and other constraints. Three cases are presented: the first two are intended to maximize employment, while the third could be useful in areas where there is a desire to investigate slow growth strategies. It should be noted that in order to maximize total employment it is more appropriate to maximize income rather than direct employment because of the magnitude of the income-induced effects in the area. For case I the allocation of incremental air quality concentration constraints over time may be useful in the development of economic strategies consistent with the prevention of significant deterioration and the maintenance of ambient air quality concentrations below allowable standards. For case II the use of emissions constraints is helpful in decision questions about how to spend emissions which have been allocated as a growth cushion for development in nonattainment areas.

In the definition of the objective function we seek to obtain a vector of economic output which can be interpreted as the optimal economic development strategy, but which, together with indirect and induced economic and population impact, will not violate air pollution constraints. Thus the objective function should contain only those manufacturing and service activities which can serve as an economic base.

Before proceeding it is worthwhile to discuss some of the implicit assumptions and rationale for using a linear progamming model, which is frequently adopted in preference to nonlinear models as a matter of convenience. As noted previously, the periodic revision of employment elasticity coefficients and wage rates compensates for inaccuracies of a linear employment function by, in effect, making the income function piecewise constant. Conventional pollutant projections, as well as optimization models, generally assume a linear relationship between population and combustion and automotive emissions. For many industrial processes, such as smelting, refining, grinding, painting, the assumption is quite reasonable, as noted in the publishing of emission factors (U.S. Environmental Protection Agency 1977). At worst, this assumption is conservative, that is, tends to overestimate emissions. Here, too, if warranted for specific industries, a piecewise constant output and emissions relationship could be developed. One might suspect that as changes in captial and plant equipment are made in certain energy and natural resource-intensive industries in future years, a shift towards conservation and recycling practices will tend to require that emission factors be adjusted accordingly.

Case I: Maximizing Income Subject to Ambient Air Quality Concentration Constraints

Let us maximize income from the economic activities vector subject to meeting ambient concentration increments. It should be recalled that the superscripts denote values at the beginning and end of the planning period and that the employment elasticity coefficient is assumed to remain constant during that time.

$$\begin{aligned}\text{Max } Z = \sum_{n} \frac{w_n{}^2 E_n{}^1 \underline{EE}_n}{X_n{}^1} & \left[\sum_{m} X_{nm}{}^2 + \sum_{l} V_{nl} X_{nl}{}^2\right] - w_n{}^2 E_n{}^1 \underline{EE}_n \\ & + w_n{}^2 E_n{}^1 + \sum_{y} w_y{}^2 a_y \sum_{l} V_{yl} X_{yl}{}^2 \\ & + \sum_{l} w_y{}^2 b_y \end{aligned} \qquad (10)$$

subject to

$$\begin{aligned}\sum_{n}\sum_{m} & [(X_{nm}{}^2 e_{nmp}{}^2 - X_{nm}{}^1 e_{nmp}{}^1) \\ & + (f_{nmp}{}^2 - f_{nmp}{}^1)]\, d_{mr} \\ & + \sum_{n}\sum_{l} V_{nl}(X_{nl}{}^2 e_{nlp}{}^2 + f_{nlp}{}^2)\, d_{lr} \\ & + \sum_{y}\sum_{l} V_{yl}(X_{yl}{}^2 e_{ylp}{}^2 + f_{ylp}{}^2)\, d_{lr} \\ & \leqslant i_{rp} \quad \text{(source-receptor constraints)}\end{aligned}$$

$$X_{nm}{}^2 \geqslant X_{nm}{}^1 + g_n \quad \text{(fairness constraints)}$$

$$X_{nl}{}^2 \geqslant M_n,\ X_{yl}{}^2 \geqslant M_y \quad \text{(feasibility constraints)}$$

$$\sum_{l} V_{nl} \leqslant 1.0,\ \sum V_{yl} \leqslant 1.0 \quad \text{(zero-one location constraints)}$$

where n and m denote an existing industry and establishment, respectively, l denotes a new location for existing or new industries, y denotes a new industry, p denotes the pth pollutant, r denotes the rth receptor, i denotes the allowable concentration increment (gm/m^3), e denotes the industrial process emission rate (gm/sec), f denotes the industrial combustion emission rate (gm/sec), g_n denotes economic growth factor for industry n during planning period, M denotes minimum feasible output (dollars), a, b are linear regression employment coefficients for a new industry, and other variables are as previously defined.

It should be noted that in the event the economic development strategy is to consider y new industries at l alternative locations, such as industrial parks, a set of additional terms has been added to the objective function. Lacking prior data to compute employment elasticity coefficients in the area for the new industries, a traditional Moore–Peterson (1955) linear employment function may be used for the initial planning period. Also employment data may be used as a surrogate for output data at individual establishments such that $X_{nm}{}^1 = (E_{nm}{}^1 / E_n{}^1)(X_n{}^1)$.

Some additional comments are required with respect to the set of constraints. In prior applications of linear programming applied to air quality, it has been generally assumed that the right side constraint was an annual average concentration; this assumption has been probably due to the convenience of using annual average diffusion formulae and dilution factors. However inasmuch as the short-term concentrations are frequently limiting, it will be desirable to use the statistical relationships developed by Larsen (1969) to calculate an effective annual average incremental concentration such that a short-term ambient concentration is not exceeded. Also, given the accuracy of the atmospheric diffusion models, it can be argued that areal patterns of ambient concentrations can be determined more accurately if incremental changes to existing concentrations are modeled and added to the previous existing concentrations.

The second constraint, which may be referred to as a fairness constraint, is intended to assure that existing industries are afforded an increment of air quality deterioration to allow for reasonable expansion consistent with macro- or regional economic projections. The second constraint also serves therefore as a nonnegativity constraint for existing establishments. The feasibility constraint is intended to assure that new establishments are of a minimum practical size. The zero-one constraint restricts the location of a new industry to one of the potential sites.

Maximizing Income Subject to Allowable Emission Constraints

With an areawide emissions constraint, it is not necessary to disaggregate industry outputs to individual establishments, so that the formulation of the optimization model is easier:

$$\text{Max } Z = \sum_n w_n{}^2 E_n{}^2 \underline{EE}_n \frac{X_n{}^2}{X_n{}^1} - w_n{}^2 E_n{}^1 \underline{EE}_n + w_n{}^2 E_n{}^1 + \sum_y w_y{}^2 a_y X_y{}^2 + w_y{}^2 b_y \quad (11)$$

subject to

$$\sum_n (X_n{}^2 e_{np}{}^2 - X_n{}^1 e_{np}{}^1) + (f_{np}{}^2 - f_{np}{}^1) + X_y{}^2 e_{yp}{}^2 + f_{yp}{}^2 \leqslant D_p$$

$$X_n{}^2 \geqslant X_n{}^1 + g_n$$

$$X_y{}^2 \geqslant M_y.$$

It should be noted that if this model formulation is applied in a nonattainment area it would be necessary to use exogenously an atmospheric diffusion model to determine a locational siting strategy consistent with the desire to improve ambient air quality at specific locations.

In addition to its application to problems involving non-reactive pollutants, this model formulation can also be used for the reactive precursors, hydrocarbons, and nitrogen oxides, which form the oxidants. First the allowable emissions of these pollutants is found from an exogenous nonlinear model which relates emissions to ambient oxidant concentrations. The allowable emissions, or some portion thereof if the emissions are being allocated over time, will then serve as the constraint for hydrocarbons and nitrogen oxides.

Other Constraints

While the focus of this paper is upon local economic development under air pollutant limitations, it is conceivable that there may be other constraints which may have to be incorporated into the analysis. Upper limit constraints could conceivably be based upon such factors as available water resources, labor supply, electric power, and ambient water quality concentrations. In the latter case, similar to the discussion of the photochemically reactive air pollutants, a frequent complexity is the nonlinear relationship between source discharges and ambient water quality concentrations (Spofford 1976). In this case it would again be easier to model exogenously the water quality concentrations in order to determine an allowable level of source discharges which could be added to the above linear programming model (s).

Conceivably there may be other kinds of economic constraints in addition to the ones discussed in the respective model cases. For example, it might be desired to specify a minimum amount of tax revenue to be generated by the economic development strategy. Or a minimum amount of a given economic activity might be desired in a specific location, such as an industrial park near a minority community.

Iterative Solution With Constraints

It is desired to ascertain that the vector of economic output, which is interpreted as the economic development strategy, together with indirect and induced economic and population impact does not exceed the allowable ambient air quality concentration increments. Thus after the initital computer run for the linear programming algorithm establishes the limiting pollutant and receptor, it is necessary to run the linear programming model in an iterative fashion to find the vector of economic output such that the total impact does not exceed air quality constraints.

This methodology is presented in the form of a flow chart (Figure 2). In essence the flow chart indicates that the linear programming formulation to maximize wages initially utilizes a more stringent air quality constraint than was desired ultimately. From the resulting vector of output and the definitions presented earlier, the sum of air quality concentrations resulting from the total economic and population impact is determined. This sum of concentrations is compared to the desired constraint, and the original constraint is changed successively until the sum of concentrations from the vector of direct output and the induced activities equals the desired constraint. The corresponding vector of direct economic outputs and locations will then be the optimal economic development strategy.[1]

Similarly the optimization problem may be solved iteratively in order to account for the total economic and

[1] Justification for the treatment of the "indirect" industrial supplier economic activities as area sources is needed. Because input will come generally from various suppliers throughout the urban area and it is impossible to know how much will be purchased from a given supplier by a given establishment, it is assumed that the "indirect"industrial activities and resulting emissions are evenly spread throughout the area. Alternately, one could utilize a Monte Carlo simulation approach by randomly assigning the input to given suppliers and using the resulting emissions to obtain a sampling distribution of point source concentrations at receptor locations. However, given the accuracy in the calculation of "local" input, this latter approach seems to be needlessly laborious.

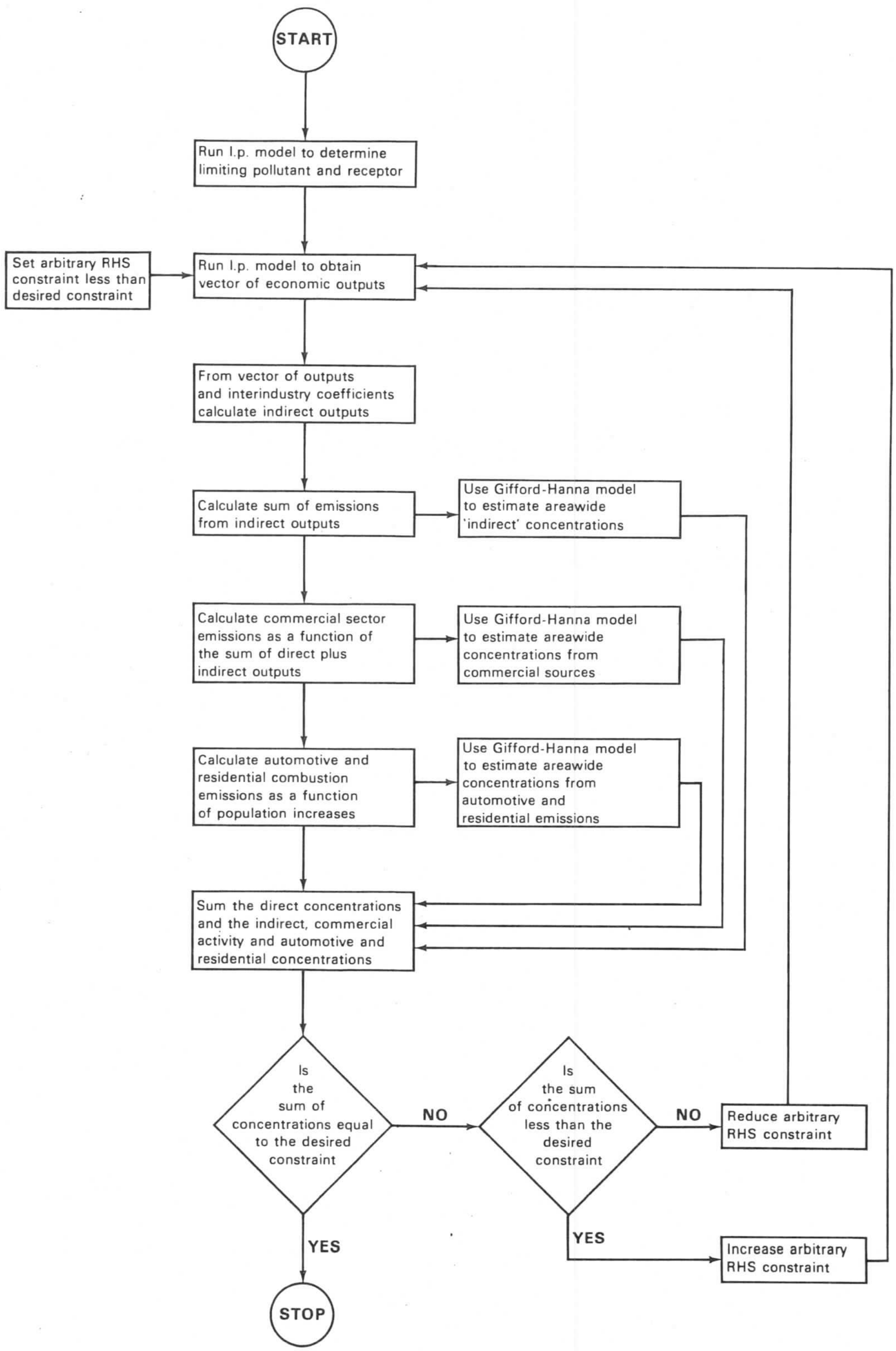

Figure 2. Flow diagram for iterative solution to linear programming problem.

population impact upon total emissions instead of ambient concentrations. The same methodology given in Figure 2 is followed except that (1) the steps finding ambient concentrations using the Gifford-Hanna model (1973) are eliminated and (2) the word emissions is substituted wherever the word concentration appears.

It should be noted that the preceding iterative methodology, with an exogenous analysis of indirect emissions based upon interidustry coefficients, considerably simplifies the objective function which would result if interindustry relations were included in the objective function. There are circumstances, however, under which the iterative solution methodology may be eliminated whereas the indirect and induced emissions are added directly to the air pollution constraints. If either regionally adjusted interindustry coefficient data are lacking, or it is desired to further simplify, conservative multipliers may be chosen to estimate outputs and emissions. Then together with the induced emissions from (5), (6), and (7), areawide concentrations or emissions, respectively, could be added as part of the air pollution constraints in cases I and II.

Case II: Minimizing Emissions Subject to Income or Employment Constraints

For cases I and II the assumed value judgment was that it is desirable to obtain the maximum degree of area income or employment that constraints upon air quality would allow. However, as has already been the case in a few areas of the United States, it is conceivable that there could be a consensus towards very slow growth to minimize air quality deterioration (and other impacts upon the quality of life). Such a philosophy might be likely to arise in areas which are either (1) highly developed, congested, polluted, and approaching or exceeding environmental carrying capacitites or (2) rural, undeveloped, and desirous of remaining that way. Hence the optimization problem may be formulated to find an economic development strategy which will minimize air pollutant emissions subject to generating a given level of income.

Because the objective of minimizing emissions could conceivably conflict with generating a certain level of income, an additional constraint upon the total allowable emissions is included. If no solution is found, either the wage constraint or emissions constraint would have to be relaxed in order to obtain a solution.

$$\text{Min} \sum_n \sum_p (e_{np}{}^2 X_n{}^2 - e_{np}{}^1 X_n{}^1) + (f_{np}{}^2 - f_{np}{}^1) \qquad (12)$$

subject to

$$\sum_n \frac{w_n{}^2 E_n{}^1 \underline{EE}_n X_n{}^2}{X_n{}^1} - w_n{}^2 E_n{}^1 \underline{EE}_n + w_n{}^2 \geqslant w$$

$$\sum_n (X_n{}^2 e_{np}{}^2 - X_n{}^1 e_{np}{}^1) + (f_{np}{}^2 - f_{np}{}^1) \leqslant D_p$$

$$X_n{}^2 \geqslant X_n{}^1 + g_n.$$

Again, the vector of outputs is used to determine exogenously the indirect and induced impacts; iterations are again performed until the sum of air quality impacts is less than the desired constraint.

Concluding Remarks

The focus of this paper has been to conceptualize and formulate methodological approaches which can be useful in different decision contexts to identify optimal local economic development strategies while meeting air quality and other constraints. An important component has been to define empirical relationships that describe indirect and induced impact upon air quality and to facilitate the estimation of changes in employment from the changes in production output.

It is hoped that other practicioners will join this author in undertaking further research which will utilize and extend these methods in actual case studies of urban economic development. An intergral part of actual case studies is sensitivity analysis in order to determine how the opitmal economic vector may vary due to uncertainties in model input, such as employment elasticity coefficients, wage rates, and pollutant emission rates. Besides determining optimal development strategies, in order to lead to a viable environmental policy such studies should also consider problems of implementation of the development strategy. These considerations should include institutional interactions in the development process and the selective use of economic incentives, such as taxes and financing, to effect the optimal development strategy.

While it is conceivable that it may not be possible to implement the optimal strategy in literal form, the optimal strategy remains useful as a point of departure for additional analysis. The optimal solution may help suggest other, suboptimal economic development vectors which (1) remain feasible with respect to meeting air pollutant constraints and (2) can be implemented more easily than the optimal solution. The optimal strategy may also serve as a yardstick by which to compare the amounts of income or employment generated by existing trends and development policies.

In hoping that this paper will help stimulate additional research and applications to further the notion that clean air and economic development are compatible, I am reminded of the statement by E. F. Schumacher, as quoted by ethicist and theologian John Taylor (1975): "what we can do, however, is to fight the growth of what is unsound and promote the growth of what is sound".

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Literature Cited

Gifford, F. A., and Hanna, S. R. 1973. *The simple ATDL urban air pollution model.* Atmospheric Turbulence and Diffusion Laboratory Contribution File No. 78 Revised. National Oceanic and Atmospheric Administration. Oak Ridge, TN.

Gorr, W., Gustafson, S., and Kortanek, K. 1971. *Optimal control strategies for air quality standards and regulatory policy.* Institute of Physical Planning Report No. 18. Carnegie-Mellon University, Pittsburgh, PA.

Guldmann, J. M., and Shefer, D. 1980. *Industrial location and air quality control.* John Wiley Interscience, NY.

Johnson, W. B., Sklarew, R. C., and Turner, D. B. 1976. Urban air quality simulation modeling. *In* Air pollution, Vol. 1. Academic Press, NY.

Kohn, R. 1970. Linear programming model for air pollution control: A Pilot study of the St. Louis airshed. *Journal of the Air Pollution Control Association* 20: 78–82.

Kohn R. 1978. Linear programming model for air pollution control. MIT Press, Cambridge, MA.

Kurtzweg, J. A., and Nelson, C. J. 1980. Clean air and economic development: an urban initiative. *Journal of the Air Pollution Control Association* 30: 1187–1193.

Larsen, R. I. 1969. A new mathematical model of air pollutant concentration averaging time and frequency. *Journal of the Air Pollution Control Association* l9: 24–30.

Moore, F. T., and Peterson, J. W. 1955. Regional analysis: An interindustry model of Utah. *Review of Economics and Statistics* 37: 363–383.

Muller, F. 1973. An operational programming model for the planning of economic activities in relation to the environment. *Socio-Economic Planning Sciences* 7: 123–138.

Muschett, F. D. 1978. More growth or better growth? *Growth and Change* 9:24–30.

Muschett, F. D. 1981. *The employment elasticity coefficient as a measure of labor intensity and its geographical variation.* Discussion Paper No. 71, Department of Georgraphy, Syracuse University, Syracuse, NY.

Muschett, F.D. (in press). Analyzing atmospheric systems. In *Analyzing Natural Systems: Analysis for Regional Residuals-Environmental Quality Management,* Daniel J. Busta and Blair T. Bower, editors. Resources for the future, Washington, DC.

Spofford, W. O., Jr. 1976. *Intergrated residuals management: a regional environmental quality management model.* RFF Reprint No. 130. Resources for the Future, Washington DC.

Taylor, John. 1975. Enough is enough. Augsburg Press, London.

U.S. Council on Environmental Quality. 1978. *The ninth annual report of the U.S. Council on Environmental Quality.* U.S. Government Printing Office, Washington DC.

U.S. Environmental Protection Agency. 1977. *Compilation of air pollutant emission factors, parts A and B.* U.S. Government Printing Office Ap-42, Washington DC.

U.S. Environmental Protection Agency. 1980. *Parallel goals: clean air and economic development/exploring new strategies for urban areas* (paper prepared for the U.S. EPA Office of Land Use and Transportation by the National League of Cities and the National Association of Counties).

Werczberger, E. 1974. A mixed integer programming model for the integration of air quality policy into land use planning. *Papers of the Regional Science Association* 33: 141–154.