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ALLOCATION OF ENERGY SUPPLIES AMONG ECONOMIC SECTORS: AN APPLICATION OF INTERINDUSTRY AND MULTIOBJECTIVE ANALYSIS

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ABSTRACT

Trade-offs between regional economic development and resource use is a question often confronting local decision makers. A multiobjective model combining linear programming and interindustry analysis is used in this article to derive levels of economic activity that maximize regional income and employment while simultaneously minimizing regional energy use. Non-dominated solutions are generated which relate regional economic activity to regional energy use. Economic sector production levels for different non-dominated solutions are derived. A suggested procedure for allocation of scarce energy resources among competing economic sectors using non-dominated solutions is presented.

INTRODUCTION

An important economic principle suggests that when a resource such as energy is in excess supply, the value of an additional unit of that resource is zero. Thus, in the early stages of economic development, attention is usually focused on output, income, and employment (economic variables) with little or no consideration of impacts on resource use. As economic growth occurs,

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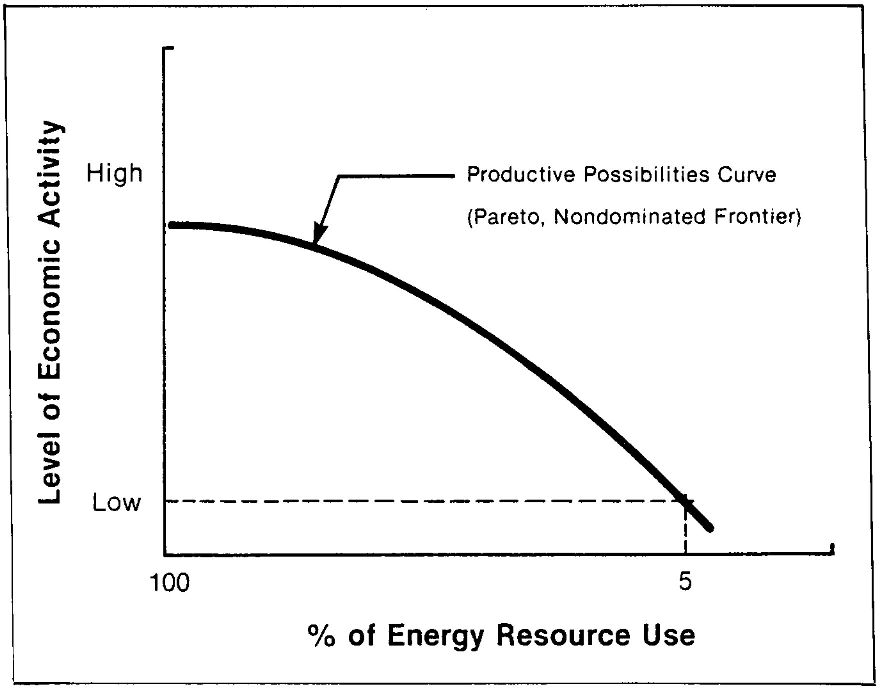

Figure 1. Trade-offs of regional economic activity and regional energy resource use.

resources such as energy appear less abundant, take on value, and occupy the attention of planners and policy makers.

As public policy makers and planners face the problems of economic growth/development and resource use, they seek the best possible information as to the consequences of their choices among development alternatives. With the Arab oil embargo and accompanying reduced energy supplies, the consequential effects on economic development from reduced energy sources has become a major problem for public policy makers. Even with current increased supplies of energy and lower energy prices, decision makers still must formulate policies if energy supplies are reduced once again. Conceptually, they face trade-offs between various levels of energy resource use and economic activity. The essence of these trade-offs may be illustrated with the use of the production possibilities curve in Figure 1.

The production possibilities curve shows the relationship between levels of energy resource use and economic activity. As shown in Figure 1, it is clearly possible to completely conserve the energy resources but at a cost of zero level of economic activity. The production or technical relationship simply reflects the use of resources in the production process and shows a proportional relationship between resource use and levels of economic activity.

From a policy maker's standpoint it would be very helpful to quantify some of the above relationships. Only then, decision makers would be able to make formal decisions regarding alternative courses of action. One way of quantifying some of these relationships is through the use of a Leontief input-output or interindustry model. Interindustry analysis portrays the interrelationships between regional economic sectors and can estimate the effects on regional output, income, and employment from various levels of resource availability. Miernyk provides an excellent discussion of input-output techniques [1]. Examples of empirical utilization of input-output models are shown in Osborn and McCray [2]; Ching [3]; and Ekholm, Schreiner, Eidman, and Doeksen [4].

Interindustry analysis has been combined with linear programming algorithms to derive levels of sectoral production which maximize or minimize a given objective such as regional income, employment, or resource use. Richardson states five situations where linear programming and input-output analysis can be useful [5]. First, in the case where an interindustry model is employed to pursue policy objectives, a linear programming format is capable of combining analysis of technical interindustry relationships and pursuance of a goal or goals. Secondly, a programming approach may be preferred if the analyst wishes to avoid the restrictions imposed by assuming fixed input-output coefficients, unchanging location patterns, and fixed trade relationships. The third possible use for linar programming models is found in interregional input-output models where a variant of the traditional linear programming transportation algorithm can be adapted to derive estimates of interregional trade flows. Fourth, linear programming procedures can be used for dynamic input-output models. The fifth and final use of a linear programming interindustry model is the efficient allocation of production factors or resources in scarce supply. Studies have been completed which incorporate linear programming and interindustry models [6-12]. In all these studies a single objective was optimized.

However, within a regional economy many objectives are formulated and expressed. The attainment of a single objective, as in linear programming, is useful but in reality decision makers are confronted with many objectives and some of the objectives are conflicting in nature. The primary objective of this article is to derive through multiobjective analysis the trade-offs in the Oklahoma economy when regional income (objective 1) and employment (objective 2) are maximized while simultaneously minimizing energy use (objective 3). Also, the multiobjective model will be used to allocate energy resources among economic sectors in Oklahoma. This allocation will be at levels that minimize the state's energy use while simultaneously maximizing income and employment in the Oklahoma economy.

DESCRIPTION OF INPUT-OUTPUT ANALYSIS AND INTERINDUSTRY LINEAR PROGRAMMING MODEL

Since Leontief's initial work in the 1930s [13], many presentations of the input-output model have appeared in literature [2,14,15]. In general, input-output models depict the regional monetary flow of goods and services through the economy. These transactions can be depicted in matrix form as:

$$X = AX + Y \quad (1)$$

where:

X is a (nxl) vector containing the dollar value of total output for each of the n sectors,
A is a (nxn) matrix of technical coefficients determined by dividing the dollar purchases of a sector from other sectors by its dollar value of total output, and
Y is an (nxl) vector containing the dollar value of final demands for each of the n sectors.

The matrix A or technical coefficients matrix is sometimes referred to as a production recipe because the column entries show the dollar value of quantity of product or service required from each sector to produce $1.00 of output by the sector heading the column.

To derive the effects to the regional economy from dollar changes in sales to final demand, (1) is solved for X:

$$X = (I - A)^{-1}\ Y \quad (2)$$

where:

$(I - A)^{-1}$ is the interindustry matrix which shows the economic impacts of adjustments by economic sectors from exogenious final demand changes in the regional economy.

The final demand multiplier is the column sum of the interindustry coefficients. The final demand multiplier for a particular sector shows the impacts on the regional economy from a $1.00 change in sales to final demand by the column sector.

Input-output multipliers are useful to estimate the change in regional output from a change in final demand for a given good or service produced in a region. However, these multipliers are inadequate if energy supplies are scarce because reducing energy supplies by one unit does not effect current sectoral output levels (i.e., sectoral shadow price is zero). By combining linear programming procedures with an input-output model, scarce resources such as energy supplies can be allocated among competing economic sectors to maximize a regional objective such as regional employment, value added, etc. If the objective function is to maximize regional income subject to the regional economy's structure, final demand delivers, and primary constraints, such as labor, the problem can be expressed as:

$$\text{Max:}\ Z(X) = C'X \tag{3}$$

subject to:

$$Y \geqslant X(I - A) \geqslant Y_0 \tag{4}$$

$$1'X \geqslant L_0 \tag{5}$$

where:

C is a (nxl) vector of direct income coefficients, i.e., ratio of sectoral income to sectoral output, elements of C are c_{ij}.
X is a (nxl) vector of sector output, elements of X are x_j.
(I − A) is a (nxn) matrix called the Leontief matrix.
$1'$ is a (nxl) vector of director labor coefficients, the ratio of sectoral employment to sector output, elements of 1 are 1_j.
Y_0 is a (nxl) vector of current final demand.
Y is a (nxl) vector of projected final demand.
L_0 is total regional labor available.
n is number of economic sectors.

Using different objective functions (e.g., maximization of employment or minimization of energy use) and equations 3 through 5, different results can be derived. It is this conflict in different objectives and the different results that can be derived for each objective that concerns policymakers. Multiobjective analysis, therefore, is used to derive solutions to problems where conflicting objectives may arise.

MULTIOBJECTIVE INTERINDUSTRY ANALYSIS

Multiobjective analysis is concerned with decision-making processes in which there are several conflicting objectives. In single-objective models all project effects are measured in terms of a single unit. That is, when maximizing profits, all project effects are measured in dollars. In multiobjective analysis, however, the decision maker pursues results as an explicit consideration of the relative value of project impacts. That is, with multiple objectives, project effects are measured in relative terms of different objectives (i.e., dollars, BTUs, etc.).

Instead of optimizing a single objective function subject to a set of constraints, multiple objective analysis finds the "best" possible values subject to the constraints of the problem. In multiple objective analysis, a single optimum solution is not sought, instead a set of "nondominated" solutions are derived. The characteristic of the nondominated set of solutions is that for each solution outside the set, there is a nondominated solution for which all

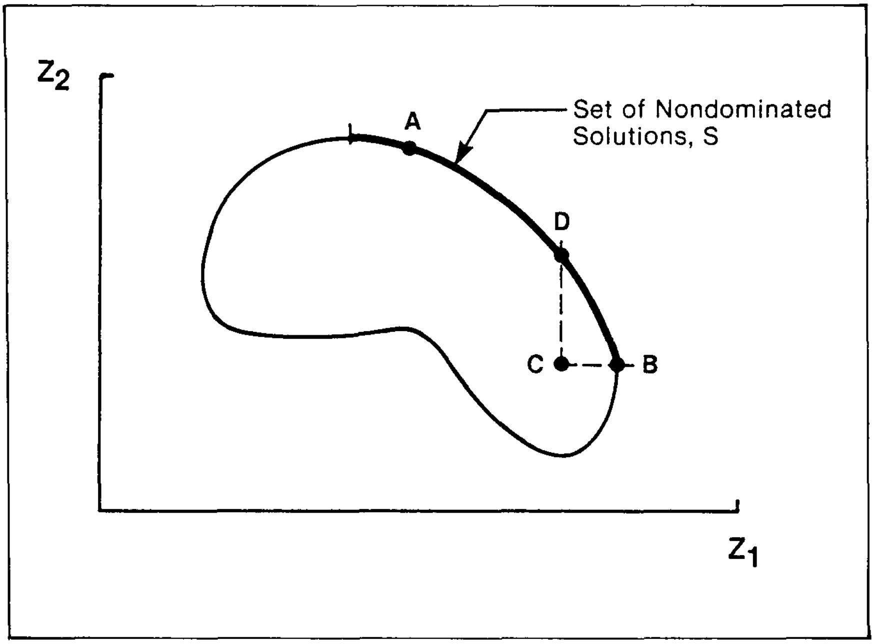

Figure 2. Graphical description of nondominated objective functions in a feasible region.

objective functions are unchanged or improved and at least one which is strictly improved.

The nondominated surface may be easily explained by Figure 2 which is a collection of feasible alternatives in a two objective problem. The axes of the figure are Z_1 and Z_2 which represent the two objective functions. The plot is for objective space as opposed to decision space where the decision variables usually denoted as X are plotted.

From Figure 2 the definition of nondominated solution can be explained with points A, B, C, and D. The point C is a dominated solution because at point B one gets more Z_1 without decreasing Z_2; point C is dominated by point B. Also, at point D one derives more Z_2 without decreasing Z_1. Therefore, the area between points A and B are nondominated solutions because as one goes from A to B an increase in one objective results in a decrease of the other objective (e.g., Pareto optimality).

In multiple objective analysis, the word "optimizing" is left out of the definition because one cannot optimize *a-priori* a vector of objective functions. Instead, the problem statement is "max-dominate" which conveys the intent to search and identify the set of nondominated solutions. The multiple objective problem, therefore, for this article is to derive the sets of nondominated solutions which maximize employment and income while simultaneously minimizing energy use in Oklahoma. The multiobjective problem can be stated as follows:

$$\text{Max-dominant:} \quad Z(X) = [Z_1(X), Z_2(X), Z_3(X)] \tag{6}$$

Subject to:

$$Y \geqslant X(I - A) \geqslant Y_0 \tag{7}$$

$$X \geqslant 0 \tag{8}$$

Where:

$Z_1(X)$ is the objective function to maximize income in Oklahoma,
$Z_2(X)$ is the objective function to maximize employment in Oklahoma,
$Z_3(X)$ is the objective function to minimize energy usage in Oklahoma, and
X, Y, Y_0 and $(I - A)$ have been defined earlier.

To derive sets of nondominated solutions in this article, the ϵ-constraint procedure is used. In the ϵ-constraint algorithm (7), the analyst specifies bounds on the objective function in a sequential manner; that is maximum allowable levels $(\epsilon_2, \epsilon_3, \ldots, \epsilon_n)$ for $n - 1$ objective functions $(Z_2(X), Z_3(X), \ldots, Z_n(X))$ are specified and the $Z_1(X)$ functions is the primary objective function.

The generalized ϵ-constraint model is formulated as:

$$\text{Max:} \quad Z_1(X) \tag{9}$$

Subject to:

$$Z_j(X) \geqslant \epsilon_j \qquad j = 2, 3, \ldots, n \tag{10}$$

$$g_k(X) \leqslant 0 \qquad k = 1, 2, \ldots, m \tag{11}$$

The ϵ-constraint algorithm can derive sets of nondominated solutions by varying the ϵ-vector. If a solution is feasible and all objective constraints are binding (that is, slack variables for the objective function are zero), then a nondominated solution exists. The formulation of the ϵ-constraint model for this analysis is:

$$\text{Max:} \quad Z_1(X) \tag{12}$$

Subject to:

$$g_k(X) \geqslant 0 \qquad k = 1, 2, \ldots, m \tag{13}$$

$$Z_2(X) \geqslant \epsilon_2 \tag{14}$$

$$-Z_3(X) \geqslant -\epsilon_3 \tag{15}$$

$$X \geqslant 0 \tag{16}$$

Where the primary objective is Z_1 (X) or the maximization of household income where boundary values will be chosen for Z_2 (X) the employment and Z_3 (X) the energy objective. The solution to equations 12 through 16 will derive sets of nondominated solutions which maximize Oklahoma income and employment while simultaneously minimizing state energy use.

INTERINDUSTRY – MULTIOBJECTIVE MODEL OF THE OKLAHOMA ECONOMY

A twenty-three-sector input-output model of the Oklahoma economy developed by Schreiner, Chang, and Flood was collapsed into a twelve-sector model [16]. The intent was to alleviate computational requirements, while aggregating monetary flows into twelve major sectoral categories.

The three objectives selected for this analysis were regional income, Z_1 (X); employment, Z_2 (X); and energy consumption Z_3 (X). Sectoral income and employment direct coefficients were derived from the study by Schreiner, Chang, and Flood, as shown in Table 1 [16]. From Table 1, the sector with the largest direct income value was the Federal Government Enterprise Sector with approximately $625,498 per $1,000,000 of sectoral output while the Fire, Insurance, and Real Estate Sector had the lowest direct income coefficient with approximately $129,776 per $1,000,000 of sectoral output. As for direct employment coefficients, the sector with the largest direct employment coefficient per $1,000,000 of sectoral output was the Wholesale and Retail Trade Sector while the Fire, Insurance, and Real Estate Sector had the lowest direct employment coefficient.

The direct coefficients for energy use were derived from a study by Flood, Chang, and Schreiner [1]. The direct energy use coefficients are in factors of 10^6 BTUs per $1,000,000 of sectoral output. From Table 1, the largest direct energy user was the State and Local Government Enterprise Sector which used approximately 99,694 $\times$ 10^6 BTUs per $1,000,000 of sectoral output while the Agricultural, Forestry, and Fisheries Sector used approximately 12,202 $\times$ 10^6 BTUs per $1,000,000 of sectoral output. These direct coefficients are used in the multiobjective formulation.

The only vectors required are final demand estimates. Final demand sectors are those sectors which do not use goods and services from other sectors as intermediate products. Instead, final demand sectors represent the final consumption of goods and services produced by economic sectors. The regional economy tries to meet these demands with the endowments of regional resources. Initial or current final demand estimates as well as procedures to estimate future final demands for Oklahoma were derived from a study of Schreiner, Chang, and Flood [16].

Table 1. Direct Income, Employment, and Energy Use per $1,000,000 of Sectoral Output in the Oklahoma Economy

Sector	*Income (dollars)*	*Employment (full-time employees)*	*Energy Use (10^6 BTUs)*
1. Agricultural, Forestry, and Fisheries	228576.03	94.64	12202.18
2. Mining and Construction	279794.23	44.65	15610.32
3. Manufacturing	180121.34	31.94	53107.02
4. Transportation, Warehouse, Communication, and Utilities	258464.14	39.86	56639.50
5. Trade	477804.96	121.67	15170.32
6. Finance, Insurance and Real Estate	129775.62	23.55	14160.62
7. Services	503511.24	109.79	13405.03
8. Federal Government	625498.01	85.42	81927.57
9. State and Local Government	156882.59	49.33	99693.53

RESULTS

For this study, the ϵ-constraint method for multiple objective analysis is used. Although the formulation of the ϵ-constraint method is rather straight forward, it is not immediately apparent how to proceed with the task of varying the ϵ_k bound. For one thing the range of feasible values for each objective is not known at the outset, and a meaningful selection of the ϵ_k is contingent upon knowledge of the appropriate range. If the ϵ_k are varied at small increments, corresponding nondominated points will result but a large number of computations may be required. On the other hand, if the ϵ_k are varied using large increments, the associated constraints may do away with the feasible region completely at some point during the analysis. Therefore, the

Cohon procedure which systematically generates non-dominated solutions will be used for the present study [18].

Table 2 shows five nondominated solutions derived through the ϵ-constraint model. For values of energy and labor availability below 446.6 $\times 10^{12}$ BTUs and 828,561 FTEs (nondominated solution 1), the model derives an infeasible solution because there are not enough resources to maintain minimal regional final demand levels. The nondominated results range from nondominated solution one with regional income of $3,875.4 million, employment of 828,561 FTEs, and energy use of 446.6 $\times 10^{12}$ BTUs to nondominated solution five with regional income of $6,087.2 million, employment of 1,293,157 FTEs, and energy use of 683.2 $\times 10^{12}$ BTUs.

Implied with these nondominated solutions is that the regional economy is able to supply the labor and energy to produce a given nondominated solution. However, if a planner is faced with limited or changing energy supplies, the nondominated solution can give a decision maker an estimate of the trade-offs between energy and regional income and employment.

If decision makers allocate scarce energy resources among alternative sectors which will maximize regional income and employment while simultaneously minimizing energy use, the multiobjective ϵ-constraint model would be a more precise tool for sector allocation. From solutions of the multiobjective ϵ-constraint model, different sectoral output levels are derived which also derive the different values that maximize regional income and employment while simultaneously minimizing energy use.

By comparing value of sectoral output for each nondominated solution, an estimate of each sector's value at each nondominated solution must be derived. The sectoral values will be derived between nondominated solutions 1 and 3 and nondominated solutions 3 and 5. DIF13 is the difference in sectoral value of

Table 2. Nondominated Solutions for Oklahoma Economy that Maximize Regional Income and Employment While Simultaneously Minimizing Costs

Nondominated Solution	*Objective Z_1 (X) Income ($1,000,000)*	*Objective Z_2 (X) Employment (FTEs)*	*Objective Z_3 (X) Energy Use (10^{12} BTUs)*
1	3,875.4	828,561	446.6
2	5,008.6	944,710	505.7
3	5,548.7	1,060,859	564.9
4	5,823.1	1,177,008	624.0
5	6,087.2	1,293,157	683.2

Table 3. Sectoral Value of Output, Differences in Sectoral Value of Output, and Sectoral Rank for Three Nondominated Solutions for the State of Oklahoma

Sector	Value of Output 1[a]	3[b]	5[c]	Value of Output Differences DIF13[d]	DIF35[e]	Sectoral Rank DIF13[f]	DIF35[g]
	($1,000)			($1,000)		(Number)	
1. Agriculture	1241.9	1814.3	1877.7	572.4	63.4	5	5
2. Mining and Construction	2129.4	3441.7	3666.9	1312.3	225.2	1	3
3. Manufacturing	4305.2	4568.2	6294.4	263.0	1726.2	7	1
4. Transportation, Warehouse, Communications and Utilities	1422.1	1908.3	2193.3	486.2	285.0	6	2
5. Trade	1718.1	2507.7	2565.9	789.6	58.2	4	7
6. Finance, Insurance, and Real Estate	1817.1	3126.7	3196.7	1309.6	70.0	2	4
7. Services	1425.1	2253.6	2314.8	828.5	61.2	3	6
8. Federal Government	100.5	152.4	158.8	51.9	6.4	8	9
9. State and Local Government	98.5	133.5	163.5	34.6	30.0	9	8

[a] Sectoral value of output for the nondominated solution for the state of Oklahoma with $3,875,400,000 of state income, 828,561 FTEs of state employment, and 446.6 X 10^{12} BTUs of state energy use.

[b] Sectoral value of output for the nondominated solution for the state of Oklahoma with $5,548,700,000 of state income, 1,060,859 FTEs of state employment, and 564.9 X 10^{12} BTUs of energy.

[c] Sectoral value of output for the nondominated solution for the state of Oklahoma with $6,087,200 of state income, 1,193,157 FTEs of state employment, and 638.2 X 10^{12} BTUs of energy.

[d] The change in sectoral value of output from nondominated solution 1 to nondominated solution 3.

[e] The change in sectoral value of output from nondominated solution 3 to nondominated solution 5.

[f] Sectoral rank by magnitude of value of output change shown in DIF13.

[g] Sectoral rank by magnitude of value of output change shown in DIF35.

output between nondominated solution 1 and 3 while DIF35 is the difference in value of sectoral output between nondominated solutions 3 and 5.

Results from Table 3 provide a basis for allocating energy among alternative users which simultaneously maximize regional income and employment while minimizing energy use. From DIF35 when energy availability increases from 564.9 X 10^{12} BTUs to 683.2 X 10^{12} BTUs, the Manufacturing Sector is the primary benefactor. In contrast, if energy availability declines from 683.2×10^{12} BTUs to 564.9×10^{12} BTUs, the Manufacturing Sector realizes the largest decline in value of output. Because of the Manufacturing Sector's low ratio of sectoral income and employment to energy use when energy availabilities are reduced from high levels, the output of the Manufacturing Sector is the largest.

Under DIF13 which has the lowest energy availability values, this column shows sectoral output changes as energy availability declines from 564.9×10^{12} BTUs to 446.6×10^{12} BTUs while regional income and employment are maximized. The sectors with the largest output declines under DIF13 are the Mining and Construction Sector and the Finance, Insurance, and Real Estate Sector. If, however, energy availability increases from 446.6×10^{12} BTUs to 564.9×10^{12} BTUs the Mining and Construction Sector is the main benefactor of increased energy supplies.

Interesting, the rank of the Agricultural Sector under these different nondominated solutions does not change. The Agricultural Sector is ranked fifth in degree of value of output increase or decline for the different nondominated solutions. For the Agricultural Sector, given current economic interdependencies, production technology, and current energy use, the major implication for the Agricultural Sector is that it will realize decreases in value of output if energy supplies decline, but the value of output reduction will not be as severe as realized in other economic sectors if energy allocations are made so that nondominated solutions prevail. With the Agricultural Sector improving its efficiency in use of energy, the effects to the Agricultural Sector may be less than currently calculated. However, the Agricultural Sector must continue its improvement in energy efficiency in relation to other economic sectors if this relationship is to hold.

The multiobjective ϵ-constraint interindustry model is an appropriate tool to measure value of energy among competing economic sectors while simultaneously maximizing regional income and employment. The conventional interindustry resource model described in reference studies by Laurent and Hite [19], Ching [3], and Harris and Ching [20] are useful descriptions of the rural economy as to interrelationships between economic sectors and resources. Another model the interindustry-linear programming model, however, derives solutions to different regional energy resource availabilities which maximize a stated regional objective, say value added, given the rural economy's production technology, economic interrelationships, and deliveries to final demand. However, in regional analysis many objectives are formulated which are conflicting in nature and decision makers must develop policies in an attempt to meet these objectives. Linear programming using only one objective falls short in deriving trade-off values. However, the multiobjective ϵ-constraint interindustry model derives solutions for different regional resource availabilities which estimates the trade-offs between different and competing regional objectives given the region's production technology, economic interrelationships, and deliveries to final demand. From these trade-offs, the decision-maker can articulate the nondominated solution that is desired.

SUMMARY AND LIMITATIONS

The primary objective of this article is to develop a multiobjective model that maximizes income and employment while simultaneously minimizing energy use in the state of Oklahoma. A multiobjective ϵ-constraint interindustry model was derived which optimally allocates energy among competing economic sectors while simultaneously maximizing state income and employment. Using results from the multiobjective ϵ-constraint interindustry model, a procedure to allocate scarce energy resources was developed which maintains nondominated solutions.

The empirical results of this study makes possible several specific conclusions unique to the Oklahoma economy. The first is that the Oklahoma economy on the whole can experience economic growth but energy availability could become a constraint. Secondly, the rank of sectoral value of output for the three nondominated solutions changed except for the Agricultural Sector. This was somewhat surprising, however, given the impacts of the Arab oil embargo on the Agricultural Sector and the corresponding thrust toward energy efficiency in agricultural production, the Agricultural Sector in the Oklahoma economy has become much more competitive for scarce energy supplies. However, the Agricultural Sector must continue its efforts in improved energy efficiency in agricultural production in order to maintain its competitive edge.

Limitations of this paper are primarily the assumptions of an interindustry model. One limitation is the assumption of fixed proportions of inputs. This restriction establishes a linear relationship between inputs and outputs. Another limitation is that the direct requirements are fixed and known. However, through time these coefficients may change and their value may be uncertain. Using procedures by Goicoechea and Hansen, a stochastic interindustry multiobjective programming model could be developed [21]. However, as Goicoechea and Hansen [21] and Harris and Goicoechea [22] have stated, the development of a probabilistic interindustry model is quite difficult and the estimation of the probability distribution for direct requirements, final demand, labor and energy requirements are quite involved.

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