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Allocative vs. Technical Efficiency, and Related Matters in Linear Programming

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The relationship between technical and allocative efficiency is examined by drawing on concepts of activity dominance in linear programming. The conclusion is reached that there is no fundamental distinction between technical and allocative efficiency. Other topics addressed in the paper, all connected by the common thread of activity dominance, include activity specification and the nature of returns to scale.

1. Introduction

Linear programming (LP) models have been used and discussed in agricultural economics for three decades or more. The opportunity to contribute further and the marginal value of contributions is probably now small.

This paper is a pot pourri of programming-related matters, joined with the common thread of activity dominance. It is, in part, intended to illustrate the use of the dominance concept, but is also intended to contribute to understanding of other programming-related concepts. The major new material for practitioners experienced in linear programming is that concerning technical and allocative efficiency.

After a brief introduction to activity dominance in Section 2, consideration is given to returns to scale in linear programming models and the ability of these models to accommodate the twin allocative and technical production problems. The discussion leads to a consideration of two further issues in subsequent sections. First, serious doubts are raised about the notion and measures of technical efficiency. Drawing on concepts of activity dominance, it is shown that allocative and technical efficiency, concepts that economists have sought to clearly distinguish, are more akin than generally recognized. Second, the question of LP activity specification is broached. Do optimal factor ratios for a production process change with the specification of resource levels in a linear programme? Can many of the activities

needed to reflect fully production opportunities be omitted?

2. Activity Dominance

The notion of activity dominance in linear programming, namely that an activity can be discarded from consideration because it is evident that it would never be needed in the optimal basis, is not new. A comprehensive formal treatment of "full information" activity dominance (or equivalently dual constraint redundancy) is available in Karwan *et al.* (1983).

Consider the following problem:

$$\begin{aligned} & \max C^F X \\ & (X) \\ & \text{subject to } A^F X \leq B \\ & X \geq 0 \end{aligned}$$

where B is an m -vector of resource levels, C^F and X are n -vectors of objective function coefficients and activity levels respectively, and A^F is an $(m \times n)$ matrix of input-output coefficients. It is assumed that problem (1) has a finite, feasible solution. Suppose that r of the activities are recognized, their objective function coefficients forming a vector C and their unit requirements for the m resources forming a matrix A with columns A_i , $i = 1, 2, \dots, r$.¹ The directions of optimization and of the inequalities are also assumed fixed as in problem (1). Activity A_i is dominated if there is no feasible solution (Z) satisfying the dual constraints of problem (1) (Drynan 1987, equation set 5):

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1. The superscript F is used in problem (1) to refer to the "full" A and C matrices, that is when $r = n$.

$$\begin{aligned}
 & a'Z - c \geq 0 \\
 (2) \quad & A_i'Z - C_i \leq 0 \\
 & Z \geq 0
 \end{aligned}$$

where a and c are the matrices A and C after eliminating the i^{th} column and element respectively, C_i and Z_i are the i^{th} elements of the m -vectors C and Z respectively. Additional information on possible shadow prices, if available, can be incorporated by the addition of further constraints on Z in problem (2).

3. LP and Constant Returns to Scale

Considerable resources have been devoted to empirically estimating returns to scale. Some would question such efforts, on the basis that constant returns to scale are inescapable: if all inputs are variable, it must always be possible to replicate the production process. Production functions must be linearly homogeneous. Observed non-constant returns to scale can reflect only imperfect measurement: all inputs cannot have been increased in proportion.

This position is accepted here *a priori*. Given the inevitability of constant returns to scale, observed decreasing returns to scale can be nothing more than diminishing returns to the variable inputs with some unspecified input held fixed, or at least not varied proportionally. Increasing returns to scale reflect either increasing returns to variable inputs, or a more than proportional increase in some unspecified input.

The linear programming model is quite instructive here. It is necessarily a linearly homogeneous model and thus consistent with the logical necessity for constant returns.² But it permits the modelling of observed decreasing returns, that is diminishing returns to variable inputs.

Any concave downwards function can be approximated arbitrarily well by a piece-wise linear approximation or polytope formed as the solution of an LP problem. That is, the function $Y = f(X_1, X_2, \dots, X_m)$ can be approximated by:

$$\begin{aligned}
 (3) \quad & Y^a = \max_{(w_i)} \sum_i Y_i w_i \\
 & \text{subject to}
 \end{aligned}$$

$$\begin{aligned}
 & \sum_i X_{ji} w_i = X_j, \\
 & \text{for } j = 1, \dots, m, \\
 & \sum_i w_i \leq 1 \\
 & w_i \geq 0.
 \end{aligned}$$

where the activity vector $(Y_i, X_{1i}, X_{2i}, \dots, X_{mi})$ represents one point on the true function. The relationship thus established between Y^a and X_j , $j=1, 2, \dots, m$, is a convex polyhedron or polytope with vertices on the true function.

The second constraint, the convexity constraint, is quite important. It forces the solution in problem (3) to be a convex combination of the various points on the function (and the origin). In the context of a production function, although it appears to be a hypothetical resource in problem (3), it is in fact a proxy for the unspecified input giving rise to the apparent decreasing returns to scale.

Without the convexity constraint, many of the activity vectors in problem (3) would be dominated. For example, suppose that there is a set of vectors corresponding to identical ratios of all inputs but differing in the level of the inputs. Suppose too that output shows decreasing returns to the specified inputs. Then only one activity would be efficient, all other activities in the set being dominated by the activity with the lowest level of inputs (and highest average output). The LP model would suggest that output could be increased linearly by scaling the specified inputs upwards. But with the convexity constraint, none of the activities in the set would be dominated by others since each either has lower input requirements or higher output than the others.

The linear programming model of problem (3) with these "points on the production function" activities and the convexity constraint is still a constant returns to scale model: if all inputs, including the convexity constraint are increased proportionally, output also increases proportionally. But with respect to the specified inputs alone, diminishing

2. One of the key assumptions identified in any text on linear programming is that of constant returns to scale. More advanced texts on linear programming will probably go on and describe how this linearity restriction can be overcome. Unfortunately, it is easy to gain the false impression that linear programming models need not involve constant returns to scale.

returns will prevail. Thus apparent decreasing returns are accommodated by modelling the implicit unspecified input(s) with an explicit proxy (set of) hypothetical input(s).

A programming model has the advantage of enforcing constant returns to scale. But the onus is on the user to account for all resources. If the convexity constraint were omitted, constant returns to scale to the specified resources alone would be wrongly imposed.

4. LP and the Technical and Allocative Production Problems

Since Farrell's (1957) pioneering work on production efficiency, economists have sought to distinguish between two production problems: the technical problem of how to get the most output from a given bundle of inputs, and the allocative problem of how to allocate inputs to various production processes to maximize the economic value of production.

Conventional production function analysis is inadequate to address both problems: the production function is defined as the relationship between bundles of inputs and the maximum output achievable (e.g. Henderson and Quandt 1958). As Dorfman *et al.* (1958) have emphasized, and Longworth and Menz (1980) have shown more recently in this *Review*, beginning economic analysis with a production function assumes away the technical problem of how inputs are to be transformed into output. This technical problem has first to be made explicit and solved before any production function can be specified, let alone used to solve allocative problems.

On the other hand, an activity based model can do precisely these things since it can encompass both the technical and allocative problems. The LP models for both problems are presented here in preparation for the subsequent discussion on efficiency matters.

Consider the technical production problem for product j . The solution to this problem defines the production function for the product:

$$(4) \quad Y_j = \max_{(w_{ji})} \sum_i Y_{ji} w_{ji}$$

subject to $\sum_i g_{kji} w_{ji} = X_{kj}$
for all k ,

$$\sum_i w_{ji} \leq 1$$

$$w_{ji} \geq 0 \quad \text{for all } i,$$

where X_{kj} is the amount of resource k available for producing product j , (Y_{ji} , g_{1ji} , g_{2ji} , ...) defines one of a number of available activities for product j , and (w_{j1} , w_{j2} , ...) is a vector of levels of activities.

The allocation problem is that of how much of each resource should be devoted to alternative products. Suppose the firm seeks to maximize the return to its fixed resources:

$$(5) \quad \max_{(X_{kj})} \sum_j C_j Y_j$$

subject to

$$\sum_j X_{kj} \leq B_k \quad \text{for all } k,$$

$$X_{kj} \geq 0 \quad \text{for all } k \text{ and } j$$

where C_j is the objective coefficient for product j , and B_k is the total availability of resource k to the firm. Now Y_j and X_{kj} are linked through the technical problems, and combining the problems, the overall problem for the firm is:

$$(6) \quad \max_{(X_{kj})} \sum_j C_j \left(\max_{\{w_{ji} | X_{kj}\}} \sum_i w_{ji} Y_{ji} \right)$$

$$\text{s.t.} \quad \sum_i g_{kji} w_{ji} = X_{kj} \quad \text{for all } k,$$

$$\sum_i w_{ji} \leq 1,$$

$$w_{ji} \geq 0$$

$$\text{for all } i,$$

subject to

$$\sum_j X_{kj} \leq B_k \quad \text{for all } k.$$

$$X_{kj} \geq 0 \quad \text{for all } k \text{ and } j.$$

For any set of resource allocations, X_{kj} for all k and j , the variables and constraints of one technical problem are independent of those in the others. Then the inner max operator can be taken outside the summation signs. The problem is then to choose S_{kj} and w_{ji} to:

$$\begin{aligned}
 (7) \quad & \max_{(X_{kj}, w_{ji})} \sum_j \sum_i C_j Y_{ji} w_{ji} \\
 & \text{subject to} \\
 & \sum_i g_{kji} w_{ji} - X_{kj} = 0 \\
 & \qquad \qquad \qquad \text{for all } k, \\
 & \sum_j X_{kj} \leq B_k \\
 & \qquad \qquad \qquad \text{for all } k, \\
 & \sum_i w_{ji} \leq 1 \\
 & \qquad \qquad \qquad \text{for all } j, \\
 & w_{ji} \geq 0 \\
 & \qquad \qquad \qquad \text{for all } i \text{ and } j.
 \end{aligned}$$

This, the standard programming formulation, then reflects both the technical and allocative problems.

5. Technical vs. Allocative Efficiency

The approaches taken by Farrell (1957), Seitz (1970), Timmer (1970) and others to the measurement of technical inefficiency differ, not only in whether they use programming methods, but in their measures. Some, including Timmer (1970), measure technical inefficiency with an "output based" measure by focussing on the shortfall in output obtained from a given bundle of inputs. Others, for example Farrell (1957), have relied on an "input based" measure and focussed on

the extent to which all inputs could be proportionately reduced and still produce a given level of output.

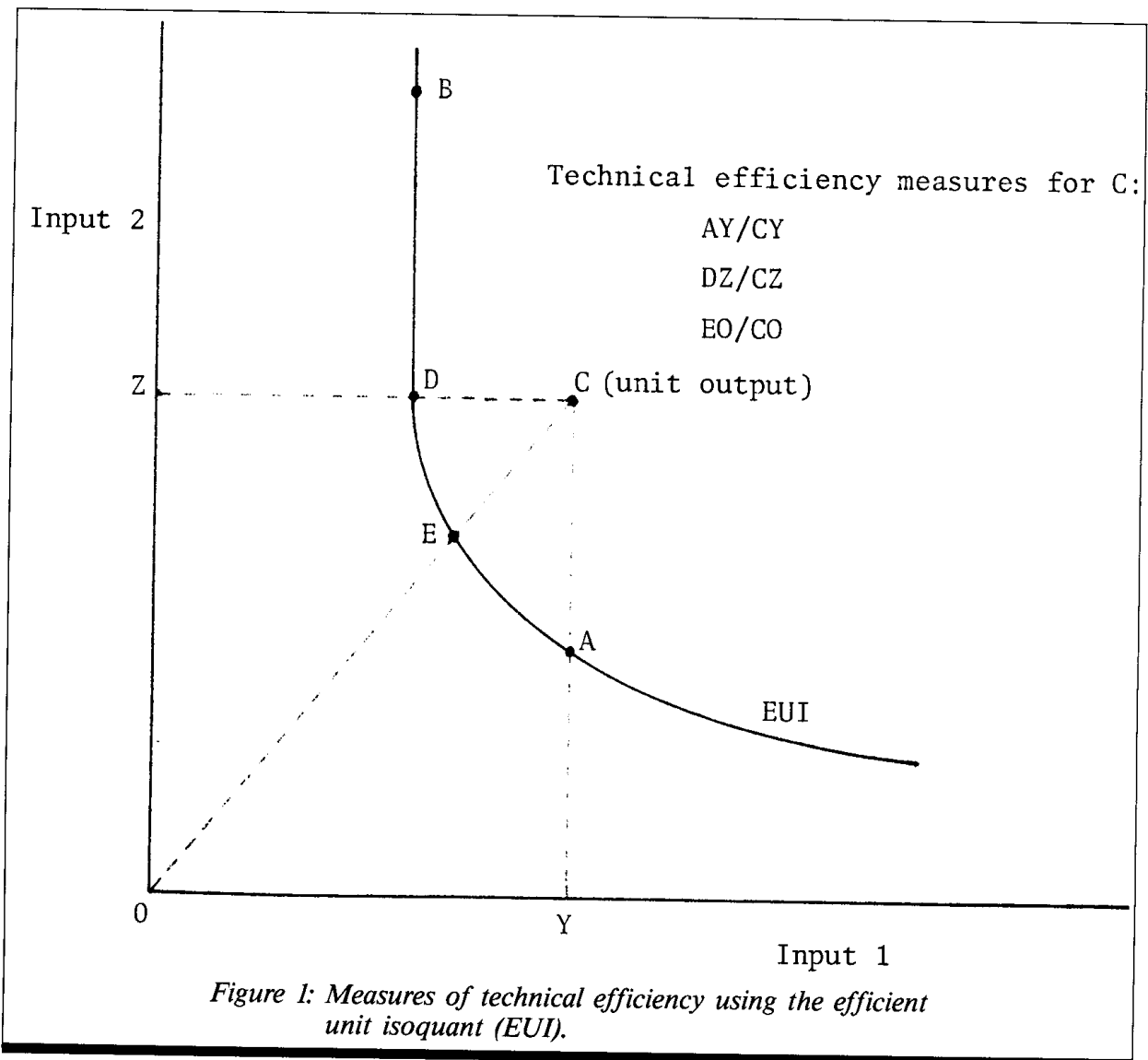
The input based and output based measures of technical efficiency are generally not identical. Only if the production function displays constant returns to scale are they the same (Fare and Lovell 1978). Further, when using an input based measure, technical efficiency can be measured in various ways by reducing a selected input, or combination of inputs, rather than by using a proportional reduction in all inputs, while maintaining output. These generalizations have been discussed by Kopp (1981) and are illustrated in Figure 1. The figure depicts the efficient unit isoquant and a series of particular activities. A, D and E are efficient activities under any of the measures. C is an inefficient activity under any of the measures, but the extent of inefficiency depends on the chosen measure. For example, C is quite inefficient relative to A but only moderately so with respect to D and E.

What about B? Because the efficient unit isoquant is vertical above D, the same output can be produced with less input than at B, in particular less of input 2 and the same amount of input 1. B is inefficient. However, with the bundle of inputs used by B, the maximum output is the unit output. Hence B is efficient. The same conclusion of efficiency is made if one focuses on a proportional reduction in inputs.

The failure of these last two tests to detect the inefficiency of B is due to a too limited comparison of B with other uses of resources, namely only to the set of combinations of other activities using exactly the same ratio of resources as activity B.

A more appropriate way to establish technical inefficiency is to focus on problem (4). Any activity which is dominated for problem (4) is technically inefficient. There is no resource situation in which the activity would be included in an optimal basis. Without knowledge of resources, and hence their shadow prices, such activities can be discarded because they waste resources in an absolute sense.

Any activity dominated in problem (4) will also be dominated in problem (7). But problem (7) may include other dominated activities, namely activities which are technically efficient for their own product but which,



given available information on product prices, cannot compete with other products under any resource (or shadow price) situation. These activities are here called "allocatively inefficient".³

Although the notion of technical efficiency appears simple enough, a closer examination leads to the inescapable conclusion that technical inefficiency is an impossibility. How can the level of output from a given bundle of inputs differ? If all inputs are fully and precisely identified, then logically only one output can result, and perfect technical efficiency is achieved as a necessity. Measured technical inefficiency can occur only through the analyst's failure to fully specify the production process.⁴ Either there must be unspecified inputs being used at different levels by the various activities, or the existing specification of input usage must not be

sufficiently revealing. In particular, the inputs may not be homogeneous.

The concept of the maximum of several possible outputs achievable from a given bundle of inputs thus has relevance only if the inputs are imperfectly specified. The analyst

3. This differs from the usual definition of allocatively inefficient activities: technically efficient activities which are not economically justified under an assumed set of prices. The definition used here allows for a range of allocative inefficiencies as the level of price information varies.

4. Those who measure technical inefficiency concede this, arguing that differences in technical efficiency reflect differences in the non-conventional inputs, namely management, technology, skills, effort, timeliness, etc. There seems little merit in choosing not to try to measure these inputs but to measure their overall impact and to describe differences in the latter by the value laden term "inefficiency".

focusses explicitly on certain defined aggregate inputs and measures technical efficiency within that context, and imposes some price information in forming the aggregates. Technical inefficiency is merely a convenient catch-all for the failure of the firm to allocate the individual inputs within aggregates correctly on the analyst's assumed prices. Any observed activity can be inefficient only because either (a) the firm has made incorrect allocation decisions about individual inputs; or (b) the analyst has assumed inappropriate prices.⁵

To see that technical inefficiency is only a form of allocative inefficiency, suppose there are r fully known activities A_j , $j = 1, \dots, r$, and that they have unit requirements A_{j1} and A_{j2} for two forms of capital, and certain requirements for resources 3, 4, ... m . A_i would be dominated if, using problem (2):

(8)

$$\begin{aligned} A_{j1}Z_1 + A_{j2}Z_2 + \dots - C_j &\geq 0 \\ \text{for all } j, j \neq i, \\ A_{i1}Z_1 + A_{i2}Z_2 + \dots - C_i &\leq 0 \\ Z &\geq 0. \end{aligned}$$

If the two forms of capital were aggregated to form resource * by assuming

$A_{j*} = A_{j1} + K A_{j2}$, A_i would be dominated if:

(9)

$$\begin{aligned} A_{j*}Z_* + A_{j3}Z_3 + \dots - C_j &\geq 0 \\ \text{for all } j, j \neq i, \\ A_{i*}Z_* + A_{i3}Z_3 + \dots - C_i &\leq 0 \\ Z &\geq 0 \end{aligned}$$

where Z is now redefined to be of length $m-1$. That is, A_i is dominated if:

(10)

$$\begin{aligned} (A_{j1} + K A_{j2})Z_* + \\ A_{j3}Z_3 + \dots - C_j &\geq 0 \\ \text{for all } j, j \neq i, \\ (A_{i1} + K A_{i2})Z_* + \\ A_{i3}Z_3 + \dots - C_i &\leq 0 \\ Z &\geq 0. \end{aligned}$$

Suppose dominance of A_i is studied assuming information on the relative shadow prices of the two forms of capital. In particular, assume that $Z_2 = K Z_1$. Then to determine dominance, a Z is sought satisfying:

(11)

$$\begin{aligned} A_{j1}Z_1 + A_{j2}Z_2 + \dots - C_j &\geq 0 \\ \text{for all } j, j \neq i, \\ A_{i1}Z_1 + A_{i2}Z_2 + \dots - C_i &\leq 0 \\ K Z_1 - Z_2 &= 0 \\ Z &\geq 0. \end{aligned}$$

5. By working with the production function, the analyst takes it for granted that the many within-aggregate allocation decision are to be made correctly on the basis of the analyst's assumed prices. One of the dangers of working with production functions is that of mis-interpretation. Errors are quite common. For example, Just *et al.* (1983) considered the case of the input "fencing" formed as the sum of goat fencing and cattle fencing. Extra fencing causes both goat and cattle output to increase. Then one can increase cattle output by increasing goat fencing alone. From a practical perspective, this appears to be nonsense. But when it is remembered that the production function shows the maximum output possible from a given set of imperfectly defined resources, it is clear that the production function does not imply that a firm could increase its cattle output by using extra goat fencing. It implies only that, if the sum total of fencing were increased and optimally allocated to fence types, cattle output would increase. The production function relates maximum output and aggregate inputs, not output and individual inputs. Only one of the many combinations of individual inputs making up the particular level of aggregate input would give the production function output.

By eliminating Z_2 , the same set of equations as in problem (10) is obtained. Thus any test of dominance to detect technical inefficiency using aggregate inputs is equivalent to a test for allocative efficiency given the prices on which the aggregates were formed.

But there are cases which appear to contradict the impossibility of technically inefficient LP activities. Suppose two activities are identical except that the first uses more fertilizer ($F_1 > F_2$), produces more yield ($Y_1 > Y_2$), and has the greater gross margin ($GM_1 > GM_2$). If the activities are specified in an LP by the vectors $(GM_i, X_{i1}, X_{i2}, \dots)$, $i=1,2$, in which fertilizer and yield are only included implicitly via the gross margins, then the second is pair-wise dominated by the first. But it would be incorrect to call the activity technically inefficient. It represents a point on the production function and this, by definition, makes it technically efficient. If the fertilizer and outputs were made explicit in the activity vectors, then neither activity would be dominated.

The dominance status changes here because of altered price information. When a gross margin is used, information on the prices of fertilizer and output is assumed. But when fertilizer and output are explicit, no information is assumed about their prices. Then shadow price situations exist in which each of the two activities could be optimal.

But suppose that F_1 were less than F_2 , and yield and gross margin were still greater for the first activity than the second. The latter then lies in the irrational zone of negative marginal returns. It is dominated both under a gross margin specification and a fertilizer/yield disaggregation. Is it technically inefficient? If using an output measure of technical efficiency, the activity must be called technically efficient, for it is on the production function, that is it gives the highest yield from the bundle of inputs. Now one might argue that by leaving some fertilizer idle, yield will be increased. But this clearly cannot happen, for if it did the production function would not show negative returns. The existence of negative marginal returns implies that there is some fixity in the system which prohibits resources being idle. Fertilizer must be used. Now if one defines an $m+1$ th resource and makes this "resource requirement" explicit as X_{m+1} , the activities must be defined by vector specifications $(Y_i, F_i, X_{i1}, X_{i2}, \dots, X_{i, m+1})$, $i=1$,

2, where $X_{1, m+1} < X_{2, m+1} < 0$. With this additional resource, again neither activity is dominated.

In summary, all activities are technically efficient if fully specified. Correspondingly, no activities are dominated if they are fully specified. Dominance arises as price information is injected into the analysis. Dominated activities are not technically inefficient but allocatively inefficient with respect to the assumed price information.

6. Specification of Linear Programming Activities

In building a programming model only efficient activities need be included. Where there is no price information, all activities describing the production opportunities must be included if the optimal solution to problem (1) is to be assured. But where prices are implicit in forming aggregates, only the so-called technically efficient activities need be retained in the model. Where further price information is available, only activities representing some part of the production space will be necessary. The difficulty, and there is no easy solution, is that of how to identify *a priori* dominated activities without having to define them fully first.

In defining an activity, suppose the ratios of all inputs except one, fertilizer, have been fixed. With a known fertilizer price and output price, the optimal fertilizer level can be determined as that maximizing the activity gross margin. Only one level of fertilizer is needed once all other inputs have been fixed. If a second, different set of ratios of the fixed factors is defined, a new optimal level of fertilizer must be determined. But again only one fertilizer level, one activity, is needed.

Nevertheless, a multitude of activities has to be defined to allow for the many possible ratios of the other factors. The major problem concerns the resources which are fixed to the firm. In most linear programmes, the shadow prices of these resources are not obvious *a priori*. The optimal factor ratios cannot be specified *a priori*, but will be those at which the marginal rates of substitution of the factors are equal to the ratios of optimal shadow prices. There is no alternative but to specify a range of activities with different ratios for the unpriced resources. For each such activity, levels of priced inputs should be

chosen (if possible) to maximize the gross margin.

But even the choice of fertilizer level may not be simple. In particular, when one alters the fertilizer level, the requirement for some other factor may necessarily change as well. For example, one of the resources which is required for a crop is cash. When more fertilizer is applied, more cash is needed. As well, more cash will be generated from the sale of extra output. If cash constraints are included with shadow prices to be determined within the model, it will be impossible to establish *a priori* an optimal fertilizer level since some of the costs and benefits of using more fertilizer are not *a priori* known. Thus one would need, for any set of fixed factor ratios (excluding cash), a series of activities with differing fertilizer (and cash) requirements.^{6,7}

There is one reason why it may be desirable to include multiple activities with varying fertilizer levels while all other resource requirements remain unchanged. Given a set of fertilizer and output prices, all except one of these activities will be dominated. But if the analyst intends to perform a price or output sensitivity analysis, that is to alter the problem information, the optimal activity may change. If only one activity were specified, the linear programme would not be able to reflect the kind of adjustments that a profit motivated firm would make.

7. Concluding Remarks

The major conclusion of this paper is that technical inefficiency cannot occur. Observed cases of technical inefficiency are either cases of allocative inefficiency or analyst error. While this may seem an extreme and not particularly useful position (just as to deny non-constant returns to scale may seem pointless to some), it is surely futile knowingly to label, interpret and wrongly draw implications from observed inefficiencies.

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6. Despite the multiple activities, there is strictly still only one fertilizer level for a set of other factor ratios. One could specify a set of ratios (including cash), and determine the gross margin maximizing fertilizer level. But the latter problem is trivial because, once the cash requirement is set, only one fertilizer level is feasible.

7. Because all choices between activities are allocative decisions, it is impossible for the economist to leave the task of defining activities to the technologist. If the economist begins his work at the time of budgeting a proposed activity, he is acceding to the technologist's judgement about prices in the formation of aggregate inputs. To do so is expecting too much of the technologist and abrogating one's responsibilities as an economist.