A Linear Programming Analysis of a Family Farm in Zealand[1]).

By Earl R. Swanson[2])

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Linear programming might be viewed simply as a technique for finding the logical implication of a set of assumptions. In the analysis which follows these assumptions deal with resources available for allo-

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cation, technical relationships (crop yields, feed requirements for livestock, etc.) and prices and costs. Once the assumptions have been explicitly stated, the problem of obtaining a solution is purely mechanical. Consequently the results can only be interpreted in close connection with the initial set of assumptions.

The purpose of this article is to illustrate the use of the technique in an analysis of the effect of milk and swine price relationships on the optimum production plan for a farm in Zealand. Since the technical data do not come from a specific farm, but are the average experience of many farmers, the results are, of course, not intended to be a prescription or recipe for operation of any given farm. Rather, our focus is on the general relationships derived from varying certain of the initial assumptions, in this case, the prices of two commodities.

I. *The Model.*

Building the linear programming model may be considered in the following steps:

1. Specification of the resources which are assumed to be fixed.
2. Choosing the products to be considered as alternatives in production.
3. Estimating the quantity of each of the fixed resources required to produce a unit of each product.
4. Developing the relationships which define the limits of production of the production possibilities.
5. Choosing the product prices and estimating the costs of resources not considered fixed (see 1 above), and constructing the income equation to be maximized subject to the limits of available resources.

We shall now consider in a rather brief manner the important elements in each of the steps outlined above.

1. An attempt was made to select the kinds of recources and to fix them at levels which would represent conditions on an average farm in Zealand.

Fixing the levels of specific resources is equivalent to choosing the length of the planning period. In this case the period is one in which it is contemplated that farm size, the family labor force, and livestock building space will not be altered.

We assume that 15 ha. of land are available to the farmer. However, of this area, 1.5 ha. are assumed to be in permanent pasture, leaving 13.5 ha. available for rotation crops. A family labor supply of 500 hours per month is assumed to be available. This might consist of, for example, the farmer, his wife, and a son. Day labor map be hired during the months of June and October to help with the beet production which has a high labor requirement during these months.

Buildings are assumed to be available to house dairy animals, swine, and two horses. Space is available for a maximum of 15 mature dairy animal uits[3]) and for 70 units of swine production[4]). However, some of the dairy building space may be used for swine production making possible a maximum increase of swine production by 50 units (a total possible maximum of 120 units insofar as building space is concerned). Such an increase in swine production would be accompanied by a decrease in building space available for dairy production of 10 mature dairy animal units. Thus it is assumed that space for 5 mature dairy animal units is specialized for dairy production and cannot be transferred to swine production. Two horses are assumed to occupy the space available for them.

2. The following products usually produced on farms in Zealand were selected to be included as possibilities in the model:

Crops	*Livestock*
Wheat	Dairy
Barley	Swine
Root crops for feed	
Rotation pasture	
Sugar beets	

3. The crop yields per hectare (from which the land requirements for each unit of crop production may be calculated) are presented in Table 1. These are average yields for the period 1950–54.

TABLE 1. *Average Crop Yields for the Islands 1950–54* [5])

Percent af Area in Root Crops	*Crop*		
	Wheat (hkg. per ha.)		*Barley* (hkg. per ha.)
10.0	34.5		34.0
30.0	41.1		40.6
Fodder Beets	*Kohlrabi*	*Rotation and Permanent Pasture*	*Sugar Beets*
(crop units per ha.)	(crop units per ha.)	(crop units per ha.)	Roots 345 hgk. per ha.
89.1	68.3	48.8	Tops 18.1 crop units per ha

[3]) One mature dairy animal unit is equal to one cow or 2.25 young animals.

[4]) A swine unit is 90 kg. of production.

Since it has been observed that farmers who have a high percent of root crops in their crop rotation scheme characteristically have higher grain yields per hectare, the average grain yields have been adjusted to indicate this beneficial effect of root crops. This assumes that the planning period is over a period of years and hence sufficiently long for this effect to occur.

The labor requirements for crop production are presented in Table 2. In this model only one technique or method of production for each crop is assumed (see footnotes to Table 2). For each crop, an attempt was made to select the most common technique followed in the production of that crop. A more complete model might include alternatives of both more and less mechanization than considered in this model.

TABLE 2. *Labor Requirements for Crops* [6]) (*man-hours per ha.*)

Period	*Wheat* [7])	*Barley* [7])	*Root Crops for feed* [8])	*Rotation Pasture* [9])	*Sugar Beets* [10])
April	–	14.1	19.9	–	17.8
May	–	–	13.2	–	4.5
June	–	–	87.8	8.0	109.7
July	–	–	13.2	8.0	4.5
August	37.6	34.2	–	–	–
September	5.8	9.4	–	–	–
October	5.8	–	41.3	–	79.4
November	–	–	39.0	–	53.0
Balance [11])	40.8	34.2	91.8	8.3	53.5
Total	89.8	91.9	305.2	24.3	322.4

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5) Landbrugsstatistik 1957, Gartneri, Skovbrug m. v. København 1958. Tables 15 and 17. Wheat and barley yields have been adjusted to reflect the percentage of root crops in the rotation according to the relationship reported in Undersøgelser over landbrugets driftsforhold. XXXXI, 2. del, København 1958, page 12.

6) Lomme-Håndbog for Konsulenter og Landbrugslærere. III. Driftsøkonomi m. v. 17.

7) Seed-bed preparation and harvesting with tractor, transport with horses, and winter theshing.

8) One-half fodder beets and one-half kohlrabi. For the fodder beets, seed-bed preparation with tractor and all other labor with horses. For kohlrabi, seed-bed preparation and root removal with tractor, and transport with horses.

9) One-third harvested as hay. Seed-bed preparation with tractor and all other preparation with horses.

10) Seed-bed preparation with tractor and all other operations with horses.

11) Non-critical operations which may be performed at nearly any time duing the year.

The feed requirements for livestock are presented in Table 3 and the labor requirements are in Table 4. Note that the per unit labor requirements decrease with size of herd. There is no completely satisfactory method for handling this type of relationship within a linear programming model[12]. In the calculation of the solutions, the medium-sized herd requirements were used.

TABLE 3. *Feed Requirements for Livestock* [13]

Feed	*Dairy* (per mature animal)	*Swine* (per 90 kg. production)	*Horses* (per mature horse)
Grain	375 kg.	323 kg.	669 kg.
Oilcake	375 kg.	–	–
Roughage [14]	2578 feed units	40 feed units	1622 feed units
Milk	89 feed units	54 feed units	–

TABLE 4. *Labor Requirements for Livestock* [15]

Period	*Dairy (per mature animal)* Size of herd (in number of mature animals)		
	7.3	*14.2*	*21.7*
Winter months (hrs. per mo.)	15.7	10.9	9.0
Summer months (hrs. per mo.)	12.6	9.0	7.5
Total annual requirement with 7 winter and 5 summer monts. (hrs.)	172.9	121.3	100.5
	Swine (per 90 kg. production) Size of herd (in number of sows)		
	1.7	*2.8*	*3.7*
Hours per month	1.37	0.96	0.62
Total annual requirement (hours)	16.44	11.52	7.44

4. We now turn to the more formal phase of describing the productior relationships in algebraic form. The central notion of linear programming is that the production complex may be broken down into individua processes[16]. A process may be viewed simply as a list of the resourc requirements per unit of product.

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[12]) Svanson, Earl R. Programming Optimal Farm Plans. I *Farm Size and Outpu Research.* Southern Cooperative Series Bulletin No. 56. Oklahoma Agr. Exp Sta. June 1958 pp. 47–58. The case of non-linear *increasing* coefficient can b handled by considering several levels of production as different „products".

[13]) Undersøgelser over landbrugets driftsforhold. XXXXI, 2. del. København 195

[14]) Straw excluded. One crop unit (see Table 1) is equal to 100 feed units.

[15]) Lomme-Håndbog for Konsulenter og Landbrugslærere. III. Driftsøkonomi m. v. 1

[16]) See Danø, Sven. Linear programming i produktionsteorien I, II og III. Natic naløkonomisk Tidskrift 93: 94–117, 205–233. 1955, 94: 47–61. 1956.

The resource requirements for each unit of the product generated by each process must be independent of the level of production of that process as well as independent of the level of production of the other processes in the model.

One may frequently encounter situations in agriculture in which this requirement is not satisfied. In the model considered here, the yields of grain are affected by the percent of root crops in the rotation. Even if this relationship were non-linear it could be approximated by defining the processes as crop combinations.

In this model the variables reprecenting the crop production processes cansist of combinations of crops rather than single crops:

x_1 =	hectares of	40%	Wh,	20%	Ba,	30%	Pa. and	10% Fb[17])
x_2 =	,,	40%	Wh,	20%	Ba,	30%	Pa. and	10% Sb
x_3 =	,,	20%	Wh,	40%	Ba,	10%	Pa, and	30% Fb
x_4 =	,,	20%	Wh,	40%	Ba.	10%	Pa, and	30% Sb
x_5 =	,,	30%	Wh,	no	Ba,	60%	Pa, and	10% Fb
x_6 =	,,	30%	Wh,	no	Ba.	60%	Pa. and	10% Sb
x_7 =	,,	no	Wh,	30%	Ba.	40%	Pa, and	30% Fb
x_8 =	,,	no	Wh,	30%	Ba,	40%	Pa, and	30% Sb

The combination of crops into a process rather than consideration of, for example, hectares of wheat as x_1, hectares of barley as x_2, etc. permits the model to take into account the effect of the percentage of root crops on grain yield. Note that total grain production is permitted to range from 30 % to 60 % of the area with complete substitution of wheat and barley at the lower limit, but with limited substitutability at the upper limit. Selection of a single rotation, that is, x_1, x_2, etc. is not necessarily required by the model; linear combinations of the crop variables are permitted.

The livestock variables are as follows:

x_9 = number of dairy cattle (mature animal units)

x_{10} = number of swine (in units of 90 kg. production)

The dairy cattle enterprise produces two products for the markat – milk and meat. In practice, there exists a possibility to shift emphasis from one product to another to respond to changing market conditions. Ideally the dairy enterprise variable x_9, should be separated into perhaps

7) Wh = Wheat
Ba = Barley
Pa = Rotation pasture
Fb = One-half fodder beets and one-half kohlrabi
Sb = Sugar beets

two or more processes which would permit choices among the alternatives *within* the dairy enterprise. Data are not readily available for the consideration of such alternatives. Consequently x_9 represents an average type of production.

Similarly, swine production might have been more realistically represented by several alternative methods of production (e. g. feeding purchased pigs and feeding pigs produced on the farm). As represented in this model, swine production is a mixture of feeding some purchased pigs and some produced on the farm.

Barley is a common livestock feed which is rather easily bought and sold. In order that these alternatives may be included, the following variables are introduced:

x_{11} = hkg. of barley sold

x_{12} = hkg. of barley purchased.

Hiring labor during June and October requires the following variables:

x_{13} = hours of labor hired during June

x_{14} = hours of labor hired during October.

Finally, a variable is needed to make space available for swine production from any decrease occurring in the number of dairy cattle:

x_{15} = dairy cattle building space transferred to swine production (in units of space required for one mature dairy animal unit).

We now turn to the statement of the relationships which define the production possibilities for this farm situation. Land available for cropping is the first relationship:

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 \leq 13.5 \text{ ha.}$$

Thus, the total land area occupied by rotation crops cannot exceed 13.5 ha.

The family labor supply of 500 hours in each month also needs to be considered. For example, the limit on production imposed by the April labor supply is as follows:

$$4.81\,x_1 + 4.60\,x_2 + 11.61\,x_3 + 10.98\,x_4 + 1.99\,x_5 + 1.78\,x_6 + 10.20\,x_7 + 9.57\,x_8 + 10.90\,x_9 + 0.90\,x_{10} \leq 500 \text{ hours}$$

The coefficients for each variable are the hours of labor required by one unit of production of that particular variable. For example, one hectare of x_1 (40% wheat, 20% barley, 30% rotation pasture, and 10% fodder beets) requires 4.81 hours during April; one dairy unit requires 10.9 hours during April, etc. The restrictions of the labor suppl in the other months may also be calculated from the data in Tables 2 and 4.

Since the hiring of labor to help during the peak labor requirement periods of June and October is a possibility in this model, the labor restrictions have an additional variable in these months. For example, the June restriction appears as follows:

$$11.18\ x_1 + 13.37\ x_2 + 27.14\ x_3 + 33.71\ x_4 + 13.58\ x_5 + 15.77\ x_6 + 29.54\ x_7 + 36.11\ x_8 + 9.0\ x_9 + 0.96\ x_{10} - x_{13} \leqq 500 \text{ hours}$$

Provision must be made for the flow of feed produced by the crops to the livestock. Two relationships are needed, one for roughage and one for barley. For roughage, we assume that it may be produced, and completely fed to livestock, or that part of it may be fed and part of it simply be produced in surplus.

In terms of feed units the roughage relationship is:

$$2251\ x_1 + 1645\ x_2 + 2849\ x_3 + 1031\ x_4 + 3715\ x_5 + 3109\ x_6 + 4313\ x_7 + 2495\ x_8 - 2578\ x_9 - 40\ x_{10} + 4076 \geqq 0$$

The constant, 4076 feed units, represents the roughage production from the 1.5 ha. of permanent pasture minus the feed requirement for the horses.

Because of its bulky nature, no provision has been made for the purchase and sale of roughage.

In contrast, the barley relation (in units of hkg.) is an accounting identity permitting sale or purchase of barley:

$$6.80\ x_1 + 6.80\ x_2 + 16.24\ x_3 + 16.24\ x_4 + 12.18\ x_7 + 12.18\ x_8$$
$$3.75\ x_9 - 3.23\ x_{10} - x_{11} + x_{12} - 13.88 = 0$$

Again, the constant 13.38 hkg. represents a fixed requirement for horse feed.

The building restricitions are as follows:

Dairy cattle building space (no. of mature dairy animal units)	$x_9 + x_{15} \leqslant 15$
Swine building space (no. of units of 90 kg. production)	$x_{10} - 5\ x_{15} \leqslant 70$
Limit on transfer of dairy building space to swine (no. of mature dairy animal units)	$x_{15} \leqslant 10$

5. In the preceding section the relationships defining the limits on production have been outlined. It remains to indicate the relative values or weights which must be assigned to each variable in order that we may develop a criterion for choosing an optimum solution from the many crop and livestock combinations that are possible with the

available resources. The criterion for choosing the optimum solution in this problem is maximization of return to the fixed resources. Thus each variable will have a coefficient indicating the „net" return, that is, the gross revenues per unit of production minus the unit costs of resources not considered as fixed..

The prices for crops and livestock (see Table 5) used are three-year averages (1954–55 through 1956–57). However, since interest lies in the effect of variation of milk and swine prices, the results which follow also include optimum systems of farming for milk and swine prices which deviate from the averages shown in Table 5. Livestock income per unit is presented in Table 6. These data include credit for manure production.

TABLE 5. *Prices for Crops and Livestock Products Sold Directly on the Market. 3 year average. 1954–55 through 1956–57* [18])

Crops	(kr. per hkg.)	*Livestock Products*	(øre per kg.)
Wheat	48.15	Sweet milk	40.4
Barley	49.17	Slaughter swine, 1st class	425.0
Sugar Beets	8.03		

TABLE 6. *Livestock Income. 3 year average. 1954–55 through 1956–57* [19])

	Dairy (kr. per mature animal)	*Swine* (kr. per 90 kg. production)
Milk	1127	–
Net sales and inventory change	354	278
Manure	45	5
	1526	283

Production costs for crops are presented in Table 7 and those for livestock are in Table 8. These production costs do not include charges for land, laber and buildings, since these resources are considered as being in fixed supply. Further, there has been no charge made for management. This means that this resource is present in adequate supply for the size af operation permitted by the land, labor, and buildings. The relation to be maximized thus represents the return (in

[18]) Undersøgelser over landbrugets driftsforhold XXXX and XXXXI 1. del Table 5.

[19]) Undersøgelser over landbrugets driftsforhold XXX 2. del, Tables 10 and 14 XXXXI 2. del, Tables 11 and 15.

crowns) to land and buildings and the labor and management of the farmer and his family:

$$- 167 x_1 + 74 x_2 - 557 x_3 + 163 x_4 - 187 x_5 + 53 x_6 - 806 x_7 - 86 x_8 + 1068 x_9 + 240 x_{10} + 49.17 x_{11} - 53.17 x_{12} - 4 x_{13} = 4x_{14} - 1138 = 0.$$

TABLE 7. *Crop Production Costs 1956–57* [20])
(excluding land, labor, and management)
kr. per ha.

	Grain	*Fodder Beets and Kohlrabi*	*Sugar Beets*	*Rotation Pasture*
Specific costs				
Seed	112	50	84	49
Fertilizer	226	448	511	176
Tractor and machinery	93	204	250	30
Equipment	195	161	234	52
Miscellaneous	59	9	140	–
Total specific	685	872	1219	307
Overhead costs				
Buildings	140	60	39	36
Taxes	88	88	97	88
Soil Improvement	26	25	38	25
Miscellaneous	27	49	61	22
Total overhead	281	212	235	171
Total production cost	966	1084	1454	478

TABLE 8. *Livestock Production Costs, 1956–57* [21])
(excluding land, labor, management, grain, and roughage)

	Dairy (per mature animal)	*Swine* per 90 kg. production)
Specific costs (kr.)		
Oil cake	230	–
Milk	81	32
Equipment	31	–
Veterinary and miscellaneous	78	7
Total specific costs	420	39
Overhead costs (kr.)		
Interest	38	4
Total cost	458	43

[20]) Undersøgelser over landbrugets driftsforhold. XXXXI, 2. del. København 1958. Tables 19, 21, 24 and 25.

[21]) Undersøgelser over landbrugets driftsforhold XXXXI, 2. del. København 1958. Tables 11 and 15.

The net return coefficient for each of the crop processes, x_1, through x_8, includes only the income from cash crops, wheat and sugar beets, while the costs represent the weighted production costs of all the crops produced in that particuler process. The income from roughage produced enters the relation to be maximized through the livestock processes, x_9, and x_{10}. Barley sold on the market appears as x_{11}, while that purchased is x_{12}. Labor may be hired at four crowns per hour (x_{13} and x_{14}). The changes necessary to make dairy cattle space available for swine are assumed to involve no cost within the limits outlined above. The constant, 1138 crowns, represents annual fixed horse costs other than feed.

The problem now is to solve for values for the variables which will maximize the net return relation presented immedeately above and also satisfy the restrictions on production outlined in section 4.

II. Results.

1. Solutions were obtained by use of the simplex method[22]). Using the *three year average prices* in Table 5, the highest return to fixed resources is achieved by Plan A in Table 9. This plan requires the cropping system x_4, which emphasizes barley and sugar beet production. The dairy enterprise occupies only the specialized space available (5 mature units), while the swine enterprise is at its maximum permitted by the building space. The expected annual return to the fixed resources when the three year average prices are used is 24, 110 crowns.

The effective restrictions on production are land and buildings. The family labor supply is adequate in all of the months except June and October, when hired labor is employed. The total labor use, including hired labor, amounts to 4075 hours. Utilization of only approximately two-thirds of the available family labor supply seems peculiar in a country in which farmers apparently work long hours. A more complete utilization of family labor might have occurred if processes having high labor requirements during the slack seasons had been included. Also it is possible that some of the overhead labor is not reported and hence could not be allocated to the specific enterprises (Tables 2 and 4).

The solution to a linear programming problem also gives estimates of the increases in income which would accompany an increase in one unit of the resources which are effective in limiting production. In this instance, an additional hectare of crop land is estimated to increase annual income by approximately 1000 crowns. Adding space for one unit of

[22]) Danø, Sven. Numerisk Løsning av Lineære Programmeringsproblemer ved Simplex Metoden. Universitetets økonomiske Laboratorium. København 1957.

swine production would add approximately 52 crowns to annual income; and space for a dairy unit would add about 260 crowns to annual income. These returns might be compared with new building costs to aid in determining the desirability of investment.

2. In this section the influence of *changes in milk and swine prices* on the optium organization of production are analyzed. In Figure 1, the horizontal axis shows a range of swine prices going from approximately 20% above the threeyear average (Table 5) to 20% below this average. Similarly, on the vertical axis, milk prices vary through about the same range.

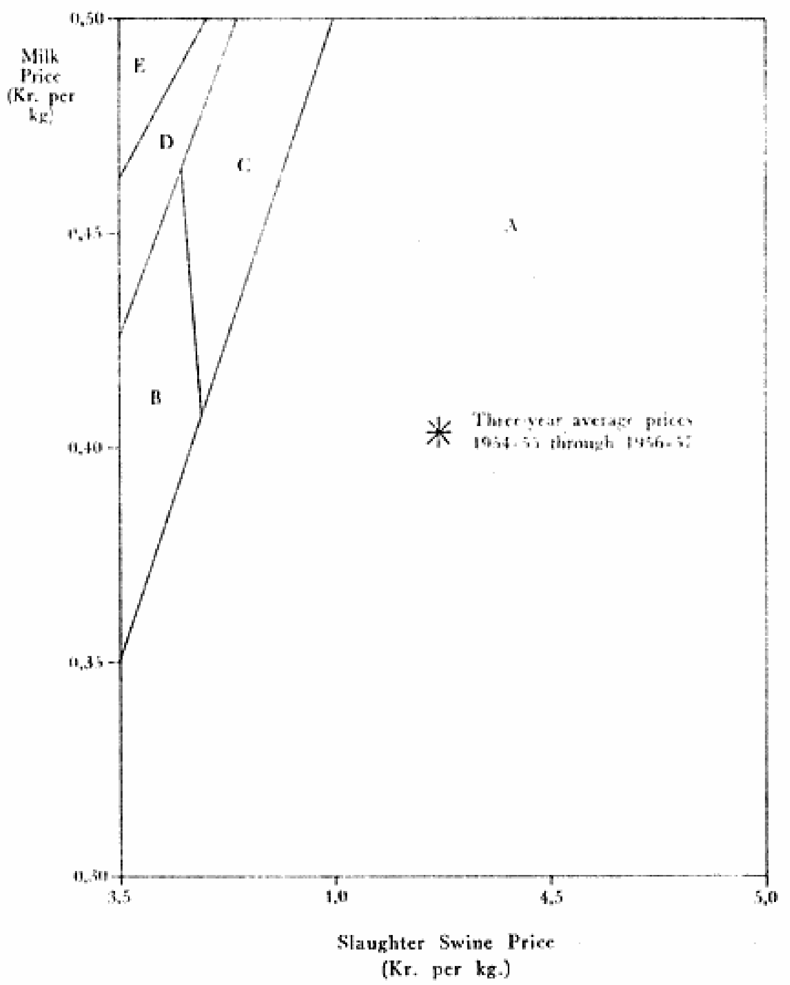

Figure 1. Price map showing optimum farm plans for varying milk and swine prices. See Table 9 for description of plans A, B, C, etc.

For the milk-swine price combinations lying in, for example, area A, the farm plan A (Table 9) is the organization yielding the highest return to the fixed resources. The boundary line between. for example, areas A and B. represents milk-swine price combinations under which plans A and B would yield the same return to the fixed resources.

TABLE 9. *Optimum Farm Plans for 15 ha. Farm with Varying Milk and Swine Prices. (See Figure 1)*

	Plan				
	A	B	C	D	E
Crops (ha.)					
Wheat	2.70	2.70	–	–	–
Barley	5.40	5.40	4.05	4.05	4.05
Sugar beets	4.05	4.05	4.05	4.05	3.70
Fodder beets	–	–	–	–	0.35
Rotation pasture	1.35	1.35	5.40	5.40	5.40
Permanent pasture	1.50	1.50	1.50	1.50	1.50
Total	15.00	15.00	15.00	15.00	15.00
Livestock					
Dairy (mature units)	5.00	5.3	13.4	14.2	15.0
Swine (90 kg. units)	120.0	109.6	77.8	30.3	29.3
Barley purchased (hkg.)	199	168	151	–	–
Hired labor (hours)					
June	166	108	183	144	143
October	8	–	43	5	–
Family labor used (hours	3951	3873	3993	3728	3818

The very favorable position of swine production is the most out standing feature of this analysis. In terms of price relationships tha have been experienced, extremely low swine and high milk prices ar needed to have an optimum plan which does not emphasize swine.

While Plan A has the maximum possible amount of swine productio (120 units), Plan E has the maximum number of dairy units (15.0). Plan C, D, and E require large amounts of roughage production for the dair cattle. This requires a shift in acreage from grain to rotation pasture anc in Plan E, a small amount of fodder beets. Because of their importanc in usual Danish cropping systems, the failure of fodder beets to compet successfully with the other crops requires explanation. Although th results indicate that rotation pasture is a more economical source c roughage, the advantage of a cultivated crop, such as fodder beets, i terms of weed control in succeeding years may be an important omitte element in the model. If farmers take this into account in their decision the linear programmer might also obtain an estimate of this relationshi and the model could be modified in the fashion indicated above for the grain yield-root crop ares relationship considered in this model (Table 1).

One might inquire concerning the reluctance of the Danish farmer to increase swine production in the direction indicated by these results. It has been suggested that his awareness of the ultimate consequences of farmers as a group also expanding production acts as a deterrent. If this is true, our model needs to be modified to embrace the total market demand schedules for the products, rather than the horizontal demand schedules assumed in this model. In such a situation, the role of the price mechanism as a reflection of consumers wants in guiding the composition of agriculturel production is somewhat different than that which usually characterizes agriculture.

Further, the competitive position of swine in this model may appear stronger than if the relative uncertainty surrounding prospective swine and milk prices were considered. (Swine prices are believed to fluctuate more than milk prices). However, it appears from this analysis that the subjective uncertainty discount would need to be substantial if this were the sole reason for refraining from an expansion of pig production. The seasonal distribution of income may also be more desirable from dairy cows than from swine. If certain minimum monthly cash income levels can be specified, this advantage of milk production can easily be incorporated into the model.

It is hoped that the rather simple analysis in this article will be suggestive of further elaborations of the model which will yield better insights into problems of adjustment of production in Danish agriculture.