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MODELLING AND EVALUATION OF A GLASSHOUSE CROPPING SYSTEM

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DEPARTMENT OF AGRICULTURAL ECONOMICS
AND FARM MANAGEMENT
Massey University, New Zealand.

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Preface

This discussion paper is a summary of a project carried out by Mr. Gerald Tapper as part of the requirements of his B.Hort.Sc.(Hons.) degree, at Massey University during 1976. The objective of this work was not to form recommendations for growers as to how glasshouse tomato crops should be managed, since sufficiently reliable data could not always be obtained. Rather, its objective was to demonstrate the way in which computerised modelling techniques can readily develop and evaluate models of glasshouse crop production systems. It is to be hoped that the publication of this Discussion Paper will stimulate further efforts in this field, with the ultimate aim of assisting the evaluation of experimental findings and their extension to producers.

Many people assisted Mr. Tapper during the course of his research. Dr. John White of the Levin Horticultural Research Centre provided experimental data, and gave of his time to discuss several aspects of glasshouse tomato culture with Mr. Tapper. Turners and Growers Ltd (Auckland) and Arlidge Bros. Ltd (Palmerston North) were of great help in the difficult task of providing market price data. Information on furnace costs was provided by Warmaire Industries Ltd and Carnahan-Andersen Ltd, and members of the Department of Horticulture at Massey University, in particular Dr. M. Nichols and Dr. K. Fisher, provided much helpful advice. The assistance provided is gratefully acknowledged. Dr. A.N. Rae, Reader in Horticultural Economics supervised the project and anyone who wishes to comment on the paper or have further information should contact him.

A.R. Frampton,
Professor and Dean of
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Contents

1. The Systems Approach

Production of horticultural crops in the protected environment of a glasshouse should lend itself readily to a "total system" approach to its evaluation. Not only do individual crops relate one to the other in terms of rotations, timing of production and competition for limited land, capital and labour resources, but the quantity and quality of yield obtained per unit of glasshouse space will depend upon many interrelated factors. These would include the composition of the glasshouse atmosphere, heating, soil moisture and nutrient status, plant spacing and training, incidence of disease and so on.

For some years, research scientists have been conducting experiments and gathering data to test various hypotheses about the nature of such relationships between the level and quality of output, and the level and quality of certain selected inputs. The next step should be to piece this data together in an attempt to model the total system. If this step of model synthesis can be successfully accomplished, then various approaches to managing the total system may be evaluated. This is the so called "systems approach", which contrasts with the more traditional approach of evaluating different management practices with respect to isolated parts of the system, without proper recognition of the impact of such management practices on the performance of other (related) parts of the crop production system.

In this study we attempt, in a modest way, to illustrate how a glasshouse production system can be synthesised and evaluated, making use of modern computerised, modelling techniques. Emphasis will be on the types of relationships that were modelled and data requirements, and the results that were achieved. Little emphasis will be placed on the technical aspects of computer modelling, since these have been adequately covered, for both animal and crop production systems, elsewhere [1 and 2].

2. The Glasshouse Cropping System to be Studied

The basis of the systems model was a glasshouse vegetable cropping unit in the Otaki-Levin region. It consisted of two unheated glasshouses, each measuring 12 m x 44 m, and a two-man labour force, one of whom was the owner and the other, a full-time employee. Within these bounds, the model was designed to measure the response of tomato production to various levels of three factors which are controllable by management. These are

(1) plant spacing
(2) heating regimes
(3) the timing of production.

The manager of a heated cropping system must make a choice from among alternative heat sources, and our model recognised the following

(4) heating with coal-fired furnaces
(5) heating with oil-fired furnaces.

We also included a second type of crop production, namely

(6) lettuce production

to illustrate the way in which an integrated systems model can easily describe and evaluate competition between different crops for the same resources.[1]

Because we did not obtain data that specified the relationships between tomato yield and levels of other variables that are under managerial control, such as soil nutrient and moisture levels, the model could not evaluate various fertilisation or irrigation policies. Instead, we adopted commonly-observed commercial practices with respect to all management decisions except those listed as (1) - (5) above.

One advantage of computerised modelling of crop systems is that the most profitable management decisions can be evaluated extremely rapidly. Even in this relatively simple model, the various options with respect to spacing, heating, time of production and heating fuel gave rise to 26 methods of tomato production. Further, each of these alternatives is competing with lettuce production for glasshouse space and labour, giving rise to an even larger number of glasshouse use patterns.

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1 However, detailed attention will only be given to the manner in which experimental and other data relating to tomato production was synthesised into a systems model. The input-output data relating to the lettuce crop is summarised in the appendices.

3. The Tomato Yield - Input Relationships

3.1 Levels of the input variables

Two plant spacings were investigated:

S1 0.2322 m^2/plant (2270 plants per house)
S2 0.2787 m^2/plant (1894 plants per house).

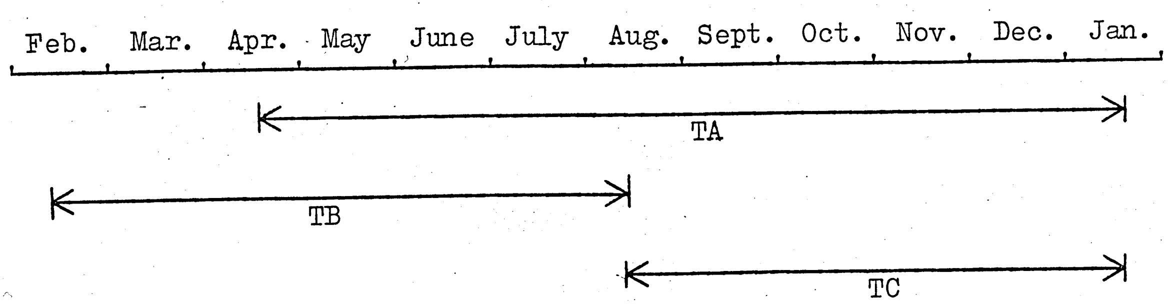
The second spacing (S2) is that commonly used by commercial tomato growers in Auckland, while S1 is a closer spacing than is normally adopted in commercial production.

Three different heating regimes were examined. All crops were ventilated at a day-time temperature of 21°C, but the three different night-time heating regimes were:

H1 A minimum night glasshouse temperature of 13°C
H2 A minimum night glasshouse temperature of 5°C
H3 No heat applied at any time.

Heat regime H1 would be considered as a heated crop in the commercial situation, although night heating to a minimum of 15.5°C is quite common. The second heat regime would be considered as heating only for frost protection.

Three time periods for tomato cropping were considered. These are approximately the time periods which are utilised in commercial tomato production.[2] They are as follows:



2 They also correspond to the time periods which were followed at Levin Horticultural Research Centre in their work on glasshouse tomato production, on which the yield data of this study was based.

TA A crop planted in mid-April and harvested from either the beginning of July or mid-July, until mid-January, depending on whether the crop was grown under heat regime H1 or H2, respectively.

TB A crop planted in mid-February and harvested from either the beginning of May or mid-May through until early August, depending on whether the crop was grown under heat regume H1 or H2, respectively.

TC A crop planted in mid-August and harvested from either the end of October (heat regime H1) or the end of November (heat regime H2 or H3) through until mid-January.

3.2 Yields

3.2.1 Annual crop yields

Yield data were based on results from experimental heating trials conducted at the Levin Horticultural Research Centre [6]. Crops grown in these experiments were produced on a commercial scale, so the yields obtained could also be expected to result from commercial production under the same husbandry practices. The variety used was Eurocross BB, transplanted when six weeks old. In all trials, the houses were ventilated when the daytime temperature reached 21°C.

Table 1 gives the level of yield for each level of the three input factors. The research trials used the second spacing (S2), and this study makes the assumption that increasing the plant density per house to that of spacing S1 would have little effect on average yields per plant.

Heat regime H3 could sensibly be employed only during the August-January (TC) cropping period. The expected yield from such a crop would not normally differ from that of a crop grown over the same months but under heat regime H2, which involves heating only for frost protection. However, the risk of losing the crop due to a late frost is much greater for the unheated crop. An analysis of meteorological records showed that a frost severe enough to kill young plants occurred with a frequency of once every 10 years. Therefore the yield from the unheated crop was estimated to average 10 percent less than the frost-protected heated crop grown over the same months.

Table 1 Saleable Tomato Yield (tonnes per house)

Cropping time period	Heat regime	Yield per plant (kg)	Yield per house Spacing S1 (tonnes)	Yield per house Spacing S2 (tonnes)
TA	H1	4.348	9.869	8.236
	H2	3.958	8.984	7.498
TB	H1	1.957	4.442	3.706
	H2	1.837	4.169	3.479
TC	H1	3.317	7.529	6.283
	H2	3.178	7.213	6.019
	H3	2.860	6.492	5.417

3.2.2 Monthly distributions of yields

The effect of heat on tomato yields is twofold. First, it affects the total yields and second, it affects the distribution of yields over months by decreasing the time lapse between planting and the first harvest. Generally the more heat that is applied, the earlier will be the commencement of harvest. It is important that this aspect of tomato production be recognised in the model. Since tomato prices follow a regular seasonal cycle, high early-season prices could well allow a substantial level of heating to be profitable.

Data on monthly yield distributions for the various combinations of input levels were not readily available. Hence, the yield distributions given in Table 2 were adapted from yield distributions recorded from somewhat similar glasshouse tomato crops at the Massey University Vegetable Unit. The yield distributions are shown in the table as the percentage of the total yield resulting from a given cropping time period and heating regime, that would be expected to be harvested in each month of that cropping period.

Table 2 Percentage of Total Yield Harvested by Month

Month	TA		TB		TC		
	H1	H2	H1	H2	H1	H2	H3
May			25	10			
June			30	40			
July	10	5	35	40			
Aug.	15	15	10	10			
Sept.	20	20					
Oct.	20	20			5		
Nov.	15	20			30	5	5
Dec.	15	15			45	60	60
Jan.	5	5			20	35	35

Note: Plant spacing did not affect the distribution of total yield over months, for any given cropping period and heat regime.

4. Estimation of Average Monthly Heat Requirements

4.1 BTU requirements

To allow estimation of the fuel quantities required to maintain each heating regime, the required quantity of heat in terms of BTU per month must first be calculated for each heat regime. Nichols [4] describes some approaches to this problem, and a modification of one of these methods was developed in this study.[3] This involves a simple method of calculating the number of degree days required to maintain a desired glasshouse air temperature relative to the outside screen air temperature, using the average monthly temperature data of Table 3, and is detailed in Appendix A. Results appear in Table 4, and indicate the number of BTU that would be required each month, on average, to maintain an internal glasshouse temperature at either heat regime H1 or H2.

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3 This modification was developed by the senior author.

Table 3 Average Monthly Temperatures (°F) - Levin (1963-74)

Month	Absolute minimum recorded for each month	Mean maximum temperatures	Mean minimum temperatures	Mean of the maximum and minimum
January	39.4	70.1	54.5	62.4
February	43.4	72.2	55.4	63.8
March	36.8	69.9	53.5	61.6
April	33.1	64.5	49.1	56.8
May	29.6	59.4	44.5	51.9
June	27.6	55.5	40.8	48.1
July	27.2	52.7	39.7	46.2
August	28.0	56.0	41.5	48.7
September	30.2	58.5	44.9	51.7
October	30.1	61.3	47.2	54.2
November	35.7	64.4	49.8	57.1
December	41.9	68.6	53.2	60.9

Source: Levin Horticultural Research Centre

Note: Expressed in °F as all heating calculations involve formulas based on °F and BTU.

Table 4 Number of BTU Required to Maintain the Internal Glasshouse Temperature at the Indicated Heat Regimes

Month	Heat regime H1	Heat regime H2
January	14 500 000	-
February	9 700 000	-
March	18 100 000	900 000
April	30 000 000	2 600 000
May	50 400 000	7 000 000
June	65 000 000	10 500 000
July	77 300 000	13 300 000
August	63 800 000	10 000 000
September	50 500 000	6 200 000
October	43 700 000	5 600 000
November	28 100 000	1 700 000
December	19 000 000	800 000

4.2 Furnace size requirements

It was calculated that the total heat loss per 1°F rise in the glasshouse air temperature over the outside air temperature was 13 855 BTU per hour, for a 12 m x 44 m house.

Given that the lowest temperature recorded at Levin between 1963 and 1974 was 27.2°F, then maintaining a glasshouse at heat regime H1 (13°C or 55.4°F night temperature) would require an expected maximum temperature lift of

$$55.4 - 27.2 = 28.2°F.$$

Thus the size of furnace required to enable a 28°F lift in temperature was

$$13\ 855 \times 28.2 = 390\ 711 \text{ BTU/hour}.$$

This was approximated in the model as one furnace of 400 000 BTU/hour capacity per house.

For the second heat regime (5°C or 41°F night temperature), the maximum temperature lift was expected to be

$$41.0 - 27.2 = 13.8°F.$$

To provide such a temperature lift, the furnace must have a capacity of

$$13\ 855 \times 13.8 = 191\ 199 \text{ BTU/hour}.$$

This was approximated in the model by a single furnace of 400 000 BTU/hour capacity to be shared between the two houses.[4]

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4 The installation of one furnace between the two glasshouses would result in a loss of flexibility of glasshouse use, since the houses could not be maintained at different temperatures. To increase flexibility, one 200 000 BTU furnace could be installed in each house - this would be sufficient capacity to maintain heat regime H2 and would enable the two houses to be used independently. Such increased flexibility would be obtained at considerable cost, however, as the cost of installing one large shared furnace is almost half the cost of the two smaller furnaces. In this study, we did not examine the more flexible alternative further.

4.3 Fuel requirements

Two alternative fuels, oil or coal, are specified in the model. This should indicate the ease with which the modelling approach can evaluate the comparative profitability of different fuels, and trace out the effect of increases in the price of one fuel relative to another.

The quantities of fuel required each month, on average, to maintain either heat regime are easily calculated. Knowing the furnace capacities of 400 000 BTU per hour, the heat requirement data of Table 4 allow the calculation of the number of hours that a furnace must be operated to obtain the required amount of heat. Multiplication of the hours of running time by the furnace fuel consumption per hour, gives the total quantity of fuel required.

For example, to maintain heat regime H1 during May requires the generation of 50 400 000 BTU of heat. Therefore the furnace must be operated for

$$50\ 400\ 000/400\ 000 = 126 \text{ hours}$$

to produce this quantity of heat. Given coal- and oil-fired furnace consumption rates of 25.39 kg of pea grade coal and 12.71 litres of diesel oil per hour, respectively, then the quantities of either fuel needed to maintain heat regime H1 during May are

$$\text{oil} - 126 \times 12.71 = 1601 \text{ litres}$$
$$\text{coal} - 126 \times 25.39 = 3.20 \text{ tonnes.}$$

All fuel requirements are presented in Table 5.

5. The Chosen Modelling Technique

The linear programming technique[5] was employed to model and therefore evaluate the glasshouse cropping system. Put simply, this technique allows the determination of the manner in which resources available in limited quantities, in this case glasshouse space and labour, should be shared between crops so as to maximise the achievement of some particular objective.

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5 For an elementary discussion of linear programming, see [5, ch.7].

Table 5 Monthly Fuel Requirements per House for Both Heat Regimes

Month	Heat Regime H2		Heat Regime H1	
	Quantity of coal (tonnes)	Quantity of oil (litres x 10^3)	Quantity of coal (tonnes)	Quantity of oil (litres x 10^3)
January	-	-	0.920	0.460
February	-	-	0.615	0.308
March	0.057	0.028	1.200	0.600
April	0.165	0.082	1.904	0.953
May	0.444	0.222	3.200	1.601
June	0.666	0.333	4.126	2.065
July	0.844	0.422	4.907	2.456
August	0.634	0.317	4.050	2.027
September	0.393	0.197	3.206	1.604
October	0.355	0.177	2.774	1.388
November	0.107	0.054	1.784	0.892
December	0.050	0.025	1.206	0.603

The objective in this case was to maximise before-tax profits. This was achieved by maximising the difference between total revenue and total variable costs. This difference, or total gross margin as it is generally named, was calculated as

total gross margin = revenue from tomato and lettuce sales
- marketing costs
- variable growing costs
- fuel costs
- annual charge to cover capital cost of new heating furnaces.

Profit can then be estimated by subtracting fixed costs from the total gross margin. However, the maximisation of total gross margin is equivalent to the maximisation of profits, since the level of fixed costs is unaffected by the way in which the glasshouse and labour resources are used.

Starting with an initial resource inventory of two unheated glasshouses and two labour units, the linear programming technique allows the researcher to isolate the most profitable way of using those resources, in terms of the specified tomato and lettuce production alternatives. In so doing, it simultaneously determines all of the following:

(i) the maximum level of profits that can be earned from the specified resources and production alternatives,

(ii) the most profitable tomato heatimg regime,

(iii) the most profitable tomato spacing,

(iv) the most profitable time to produce tomato crops,

(v) the most profitable level of tomato production,

(vi) the most profitable level of lettuce production,

(vii) the most profitable heating fuel,

(viii) the most profitable number and type of furnaces to purchase,

(ix) that the crop production programme does not require the input of more labour each month than is expected to be available,

(x) that the tomato/lettuce cropping rotations are feasible with respect to available glasshouse space, heating capabilities and timing of production.

Because linear programming models are normally solved with computers, the effect that changes in certain data values have on the most profitable production programme can be easily and readily determined. In this study, the effect of changes in the oil price relative to the coal price is evaluated to illustrate the manner in which linear programming models can be employed to generate further insight into the nature of cropping systems.

For the reader who is familiar with linear programming, details of the model are given in Appendix D, which also includes the monthly labour requirements of the various crops.[6] All data relating to tomato and lettuce prices, costs of growing and marketing tomato and lettuce crops, and heating and furnace costs, are to be found in Appendices B and C. Otherwise, all data necessary to the construction of the linear programming model is to be found in the preceding sections.

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6 Labour requirements in tomato production were based on figures given in [3] and [7]. Those of the lettuce crops were based on the senior author's experience.

6. Evaluation of the Glasshouse Cropping System

6.1 Evaluation at current fuel prices

At the time the study was carried out, on-farm prices of the two alternative fuels were:

coal : $40 per tonne
oil : $0.142 per litre.

Given these prices, the most profitable use of the glasshouse and labour resources required that

- both houses be utilised for tomato production only,
- tomatoes be grown between April and January (time period TA),
- a plant spacing of 0.2322 m^2/plant be adopted (spacing S1),
- heat be applied to maintain a minimum night temperature of 5°C (heat regime H2),
- either oil or coal be used as heating fuel,
- a single furnace of 400 000 BTU/hour capacity be purchased to service both houses.

The budget in Table 6 summarises the expected financial implications of following the above management practices. It can be seen that at the current ratio of oil to coal prices, oil is only marginally more profitable than coal as the source of heat. For practical purposes, it can be

Table 6 Estimation of Profitability for Both Fuel Types

Costs			Revenue			
	If coal is fuel ($)	If oil is fuel ($)		Sales (kg)	Price[b)] ($/kg)	Total ($)
Growing costs[a)]	658	658	July	898	0.809	726
Fuel costs			Aug.	2,694	1.168	3,147
(7.15t x $40)	286		Sept.	3,592	1.303	4,680
(3576ℓ x $0.142)		507	Oct.	3,592	1.486	5,338
Capital cost of furnace	615	378	Nov.	3,592	0.862	3,096
Totals	1,559	1,543	Dec.	2,694	0.593	1,597
			Jan.	898	0.638	573
Total gross margin =	17,598	17,614			Total	19,157

a. Plants, spray, fertiliser, string and machinery running costs.

b. Net of auctioneer's commission, vegetable levy, case and freight costs.

concluded that the current ratio of oil to coal prices is a "breakeven" one, in that by making most profitable use of either type of fuel, a total gross margin of around $17,600 can be expected.[7]

From the data provided in the solution to the linear programming model can also be obtained the monthly labour requirements of the most profitable cropping programme. This information can be usefully presented as a labour profile, as in Fig.1, which indicates those months of the year when labour demands will be at a peak. The figure reveals that the labour peak occurs during the main harvesting period of August to December, but that at no stage during the year is the available labour fully utilised.

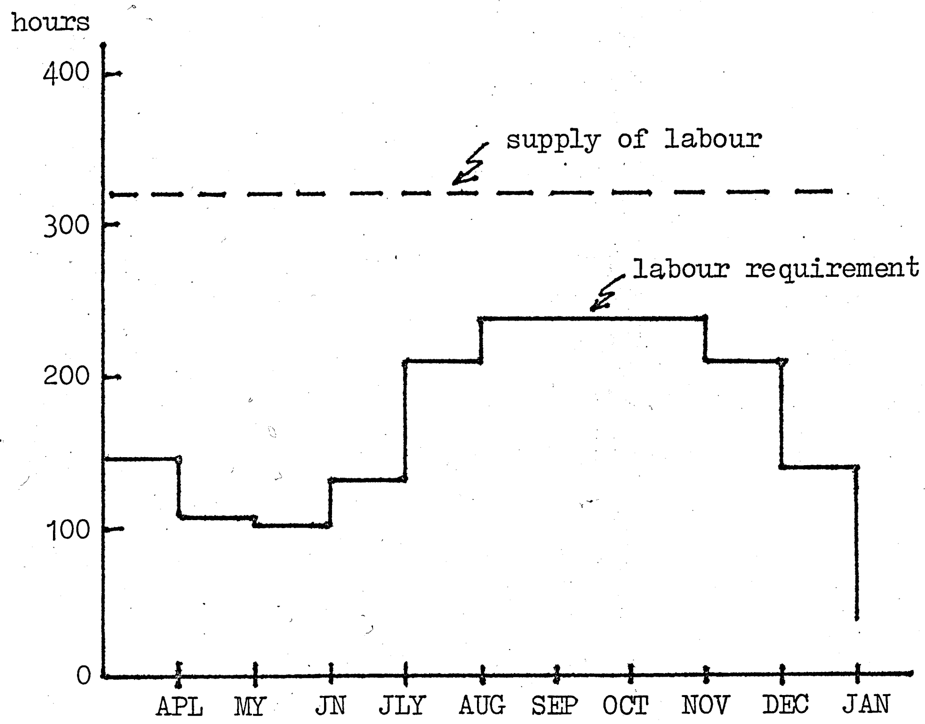

Fig.1 Profile of Labour Use

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7 To obtain a profit estimate, fixed costs (which would include for example the wages of one man and depreciation of the glasshouses and machinery) would need be deducted from this total gross margin. The remaining profit would then represent the return to the owner's labour and capital investment.

6.2 Evaluation of the cropping system for a range of fuel prices

To illustrate the ease with which the linear programming technique can generate additional useful information, prices of both coal and oil were varied to determine their effect on the choice of the production programme. It was found that even for fuel prices 15 times greater than current levels, both glasshouses should be cropped with tomatoes, planted at a spacing of 0.2322 m^2/plant (spacing S1) and grown between April and January (time period TA). For oil prices above $0.063 per litre or coal prices above $26.30 per tonne, the crop should be heated to a minimum night temperature of 5°C. However for oil prices less than $0.063 per litre or coal prices less than $26.30 per tonne, it would be most profitable to apply greater quantities of heat to maintain a minimum night temperature of 13°C (regime H1).

Figure 2 illustrates these results, and also allows the most profitable fuel to be selected for any pair of oil and coal prices. Current fuel prices, and the maximum total gross margin that can be earned at those prices, are indicated in the figure by the points A and B. Clearly, both fuels are equally as profitable. Should the price of oil rise to $250 per 1000 litres, however, the most profitable use of that fuel will fall below the total gross margin that can be earned with coal as the heating fuel available at $40 per tonne (points D and A). Hence coal would be the more profitable fuel, and reference to the decision rules shows that since the coal price is greater than $26.30 per tonne, heat regime H2 should be adopted. This comparative analysis to select the most profitable fuel and heating regime can be carried out for any pair of fuel prices shown in the figure.

It needs to be pointed out that this analysis remains valid only so long as no other data values in the model undergo change. As other values, such as tomato prices, almost certainly will change over time, the systems model would require adjustment and re-evaluation to keep results relevant to current conditions.

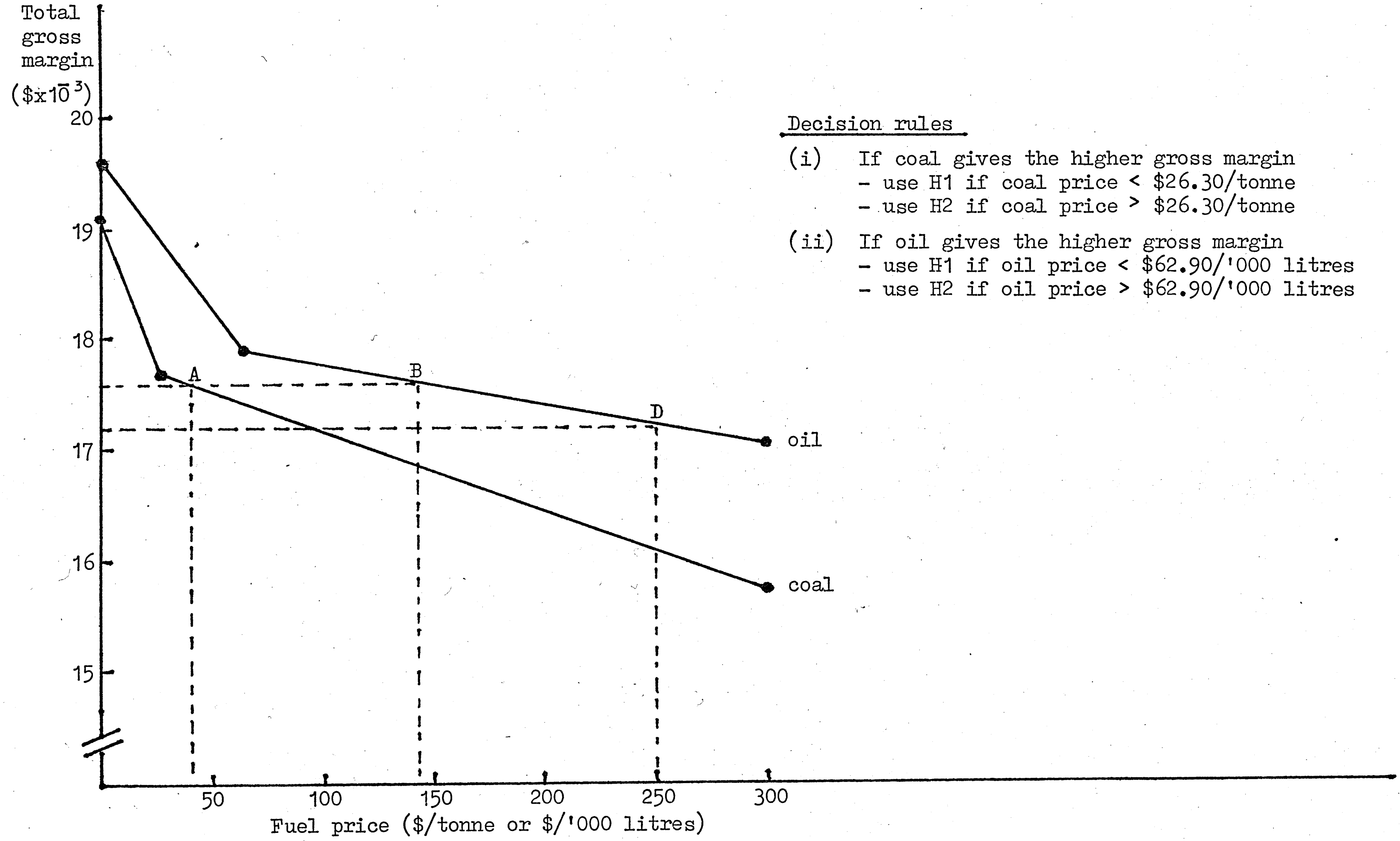

Figure 2 Selection of Heating Regimes for a Range of Fuel Prices

7. Summary and Scope for Further Modelling

This study has indicated one way in which experimental and market data can be combined into an integrated model of a glasshouse cropping system. Mathematical analysis of the model then permitted an economic evaluation of those aspects of the cropping system for which managerial choices had been specified. This systems approach meant that all such choices were evaluated simultaneously, so taking into account the various interactions between model components. This contrasts with the perhaps more traditional approach of evaluating crop performance largely in physical terms, and on a piecemeal rather than an integrated basis.

While the primary objective of the study was to illustrate the systems approach, the results obtained are of some interest also. It appeared, quite by coincidence, that at current oil and coal prices, both fuels are equally as profitable as sources of heat for the tomato cropping system described by the data of the model. This means that should oil prices increase more rapidly than coal prices in the future, then coal would become the more profitable fuel. Further, the most profitable approach to the management of the modelled cropping system, apart from the selection of fuel, is quite insensitive to further increases in fuel prices, which would have to rise by over 15 times their current levels before a rotation involving unheated tomatoes and lettuce crops became the most profitable production system.

There are a number of ways in which the model could be improved, and it is hoped that this report will eventually lead to the construction and application of such improved models of glasshouse cropping systems relevant to New Zealand conditions.

Subject to the availability of experimental data, other tomato crop management variables such as irrigation, fertilisation and atmospheric CO_2 levels could be specified in the model. This would allow a more complete evaluation of the profitability of different approaches to the management of glasshouse tomato crops. The method used to estimate heat requirements could perhaps be improved to incorporate the effects of wind and solar radiation, and to indicate the variability in monthly heat requirements from year to year. Other sources of heat, such as natural gas and electricity, could also be evaluated.

Market prices used in the model were based on information collected over only a two year period, were based partly on records and partly on the subjective estimates of experienced tomato auctioneers, and did not distinguish between tomato quality and size. Efforts presently being made by some fruit and vegetable wholesaling companies should eventually lead to more accurate and complete price data being available. In this connection, a more accurate specification of the monthly distributions of tomato yields, and the manner in which those distributions are influenced by management practices, would seem desirable.

Finally, and again subject to data availability, crops in addition to tomatoes and lettuce that could be part of a glasshouse cropping system could be added to the model. Examples might be beans, cucumbers and capsicum. This would allow the profitability of different management techniques for the various crops to be evaluated not in isolation, but in relation to the profitability of using glasshouse and labour resources in other production alternatives.

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Appendix A   Calculation of Heat Requirements

The method used to calculate the heat requirements was a modified version of the Winspear Method [4]. The formulas used are as follows:

[1] if $B < L$, then $D = 0$

[2] if $L < B < M$, then $D = \frac{1}{4}(B-L)$

[3] if $M < B < H$, then $D = \frac{1}{2}(B-L) - \frac{1}{4}(H-B)$

[4] if $H < B$, then $D = B - M$

where

D = degree days

B = required glasshouse temperature

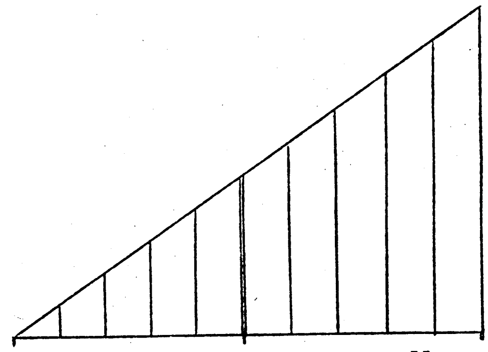
H = mean monthly maximum temperature

L = mean monthly minimum temperature

$M = (H+L)/2$.

The Winspear Method, however, can give an erroneously low heat requirement especially if the average minimum temperature is close to the desired glasshouse temperature. Then, heat required to lift the glasshouse temperature on nights when the temperature drops well below the average minimum temperature tends to be ignored.

The modification of this method comes in adjusting L, the mean monthly minimum temperature, to be more sensitive to the absolute minimum temperature and in appreciating the pattern of temperature movements in a twenty four hour period. It involved calculating heat requirements using the formula previously listed, but dividing up the temperature difference between the absolute minimum and mean of the monthly minimum into five equal temperature sections, and similarly for the temperature difference between the mean of minimum and mean of maximum:



This provides a more accurate basis for calculating heat requirements. The following examples demonstrate the system used.

For example in the month of June (from Table 3)

H = mean of maximum = 55.5°F

L = mean of minimum = 40.8°F.

The range between these two temperatures is 14.7°F.
The absolute minimum is 27.6°F.
The difference between the mean of the monthly minimum and the absolute minimum is 40.8 - 27.6 = 13.2°F.
This difference is divided by 5 giving a unit of increase of 2.64°F.

Table A.1 shows how the heat values were derived, by calculating the heat requirement if heat regime H2 is used, (i.e. B = 41°F).

Table A.1

+2.64°F

	(A)	(B)	(C)	(D)	(E)	(F)
B	41	41	41	41	41	41
L	27.6	30.27	32.88	35.52	38.16	40.80
H	42.3	44.94	47.58	50.22	52.86	55.50
M	34.95	37.59	40.23	42.87	45.51	48.15

14.7°F

To each one of these sets of data (A)-(F) were applied the corresponding formula previously mentioned, to give the results recorded in Table A.2.

Table A.2

Data	Formula used	Resulting number of degree days
(A)	[3]	6.375
(B)	[3]	4.395
(C)	[3]	2.415
(D)	[2]	1.370
(E)	[2]	0.710
(F)	[2]	0.050
	Total =	15.315

This subtotal of 15.315 degree days was divided by ten (because ten temperature divisions were made per 24 hour period), multiplied first by the number of days in the month (30) then by the hours in a day (24), to yield a figure of:

1103 BTU per sq.ft of glass per the month of June.

Since each house consists of 9451 sq. ft. of glass, the number of BTU of heat required per house per month of June is approximately 10 500 000. This figure then appears in Table 4.

Appendix B Derivation of Market Price Data

B.1 Tomato prices

Turners and Growers Ltd, Auckland and Arlidge Bros., Palmerston North, provided records covering the two years 1975-76. These allowed average daily prices to be derived, which were aggregated into monthly averages. During the four months October to January, average prices in Palmerston North were noticeably higher than Auckland prices. Thus a marketing strategy was devised for the model, which required the crop to be allocated evenly between these two centres during the months October to January, with the entire crop being sold in Auckland during all other months. Therefore the October to January prices in the model were averages of Auckland and Palmerston North prices.

The gross prices are given in the first column of data in Table B.1. The net prices were determined by subtracting the wholesaler's commission, vegetable levy, case and freight costs from the gross prices.

Table B.1 Tomato - Gross and Net Prices ($/kg)

Month	Gross wholesale price	Marketing costs[a]	Net price to producer
May	0.75	0.120	0.630
June	0.80	0.125	0.675
July	0.95	0.141	0.809
Aug.	1.35	0.182	1.168
Sept.	1.50	0.197	1.303
Oct.	1.70	0.214	1.486
Nov.	1.00	0.138	0.862
Dec.	0.70	0.107	0.593
Jan.	0.75	0.112	0.638

a. Commission, levy, case and freight costs.

B.2 Lettuce prices and revenues

The lettuce crop consisted of two plantings, one harvested at the end of April, the other in late July-early August. After examination of the daily range of lettuce prices provided by Turners and Growers Ltd of Auckland, and following the assumption that glasshouse lettuces would be of such quality as to command a price in the upper quartile of that range, prices of $4.00 per carton in April and $7.20 per carton in July-August were estimated.

Table B.2 gives all price and marketing cost data for the lettuce crops, from which can be derived the gross and net revenues per house. Each lettuce crop was estimated to provide a yield of 197 cartons of produce.

Table B.2 Lettuce Prices, Yields and Revenues

Crop	Price ($/carton)	Yield (cartons/house)	Gross revenue	Marketing costs[a] ($/house)	Net revenue
1st	4.00	197	788	251	537
2nd	7.20	197	1418	315	1103
			Total net revenue		1640

a. Commission, levy, case and freight costs.

Appendix C Derivation of Production Cost Data

C.1 Tomato production costs

Table C.1 gives the production costs for each of the various combinations of levels of the three factors, time of production, heating and spacing. Not included in these costs are the fuel and marketing costs, which have been covered elsewhere. The costs of soil sterilisation and production of a cover crop were also not included as they were common to all of the glasshouse crops, and could therefore be treated as fixed costs.

Table C.1 Tomato Variable Production Costs ($/house)

Cropping time period	Spacing	Plants	Spray	Base fert.	Fert. side dressing	String	Machinery running	Total
TA	S1	113	61	29	62	15	49	329
	S2	95	51	29	51	12	45	283
TB	S1	113	37	29	41	15	33	268
	S2	95	31	29	34	12	30	231
TC	S1	113	33	29	34	15	27	251
	S2	95	28	29	29	12	25	218

Note: Choice of heat regime did not affect the level of these production costs. (It would, of course, influence fuel costs and, through its effect on yields, marketing costs).

C.2 Lettuce production costs

Variable production costs for lettuce were estimated as:

base fertiliser	$8 per house
seed	36
machinery running	12
spray	6
total variable costs	$62 per house.

The lettuce gross margin was calculated as the gross revenue net of marketing costs (Appendix B) less variable costs:

lettuce net revenue	$1640 per house
less variable production costs	- 62
lettuce gross margin =	$1578 per house.

C.3 Furnace costs

Two companies provided data on the total costs of purchasing and installing 400 000 BTU/hour oil and coal furnaces.[1] These costs, which covered such items as the initial purchase cost, installation charges and the cost of ancilliary equipment such as fuel tanks and flue systems, totalled $2685 for the oil-fired furnace and $4500 for the coal-fired furnace. Since the furnaces have a useful life of perhaps 15 years these total costs must be spread over the life of the furnaces. This was achieved by converting the total costs to annuities with the following formula:

$$A = TC \left[\frac{r(1+r)^t}{(1+r)^t - 1} \right]$$

where A = the annual furnace cost
TC = the total cost of the furnace
r = an interest rate (0.10), and
t = estimated life of the furnace (15 years).

This gave annual costs for the oil and coal furnaces of $353 and $590 respectively. To each cost was added a quoted yearly charge for inspection and maintenance of $25, which increased the annual costs to $378 for the oil furnace and $615 for the coal furnace.

1 These companies were Warmaire Industries Ltd (oil furnaces) and Carnahan-Andersen Ltd (coal furnaces). Costs quoted were as at June 1976.

Appendix D The Linear Programming Model

A copy of the linear programming model appears as Table D.1. The columns and rows have been numbered, and are briefly described below.

D.1 The activities

Columns 3-6 describe the furnace activities according to the notation:

CSF: Coal Share Furnace, or ONE furnace shared between both houses;

and CIF: Coal Individual Furnace, or one furnace for each house as is required for Heat Regime H1.

Similarly,

ØSF represents Oil Share Furnace

and ØIF represents Oil Individual Furnace.

Columns 7-28 describe the tomato cropping alternatives, in single house units. Each column name is a combination of one of the three cropping time periods TA, TB, TC, one of the three heat regimes H1, H2 and H3 and one of the two plant spacings S1, S2.

The notation X, Y, Z has been used to allow for a crop to be grown in a house which has greater heating capacity than is required for that particular crop. Thus where the notation X is used, this denotes the house has the heating capacity to enable heat regime H1 to be maintained, but can be used to maintain heat regime H2 simply by turning the furnace off. Where the notation Y is used both houses have heating capacity to enable heat regime H2 to be maintained, but both houses can be used to grow a heat regime H3 crop by switching off the furnaces. Where the notation Z is used, this indicates that no furnaces have been installed.

Columns 29-31 describe the lettuce crops grown during cropping time period B at heat regime H3. The notation X, Y and Z is the notation as described for the tomato activities.

Columns 32-40 describe the tomato selling activities with units of one tonne, where:

MY = May

JN = June

JLY = July

AU = August

SE = September

OC = October

NO = November

DE = December

JA = January

These selling activities allow tomatoes to be sold for a total gross revenue net of all marketing costs per tonne of tomatoes in the respective months.

Columns 41 and 42 describe the buy oil and buy coal activities respectively. The model was run twice, once with the buy oil activity and once with the buy coal activity.

D.2 The restraints

Row 1 is the objective function. Coefficients are either furnace annuities, total growing costs per house, market prices net of marketing costs, or fuel prices (see Appendix C). For the lettuce activities, the objective function coefficients are gross margins per house.

Rows 3-8 describe the glasshouse restraints, where 'pre' and 'post' refer to the use of glasshouse space before or after mid-August, respectively. For example, a crop grown in cropping time period TA occupies glasshouse space both pre-August and post-August. A crop grown in cropping time period TB uses only pre-August glasshouse space, and a crop grown in cropping time period TC uses only post-August glasshouse space.

Thus rows 3 and 4 state the initial supply of unheated (H3) glasshouse space in single house units. By installing one common furnace between each house the supply of unheated glasshouse space is converted to heated glasshouse space with the capacity to maintain heat regime H2. The rows 5 and 6 denote the supply of this type of heated glasshouse. Likewise the unheated glasshouses can each be fitted with individual furnaces thus converting the initial supply of unheated glasshouse space to heated space with the capacity to maintain heat regime H1. Thus rows 7 and 8 denote the supply of this type of heated glasshouse space.

Rows 9-17 describe the tomato yield restraints and show the distribution of total yield over the harvest months. Yields are expressed as tonnes per house.

Rows 18 and 19 are the fuel quantity restraints. The quantity of coal is expressed as tonnes per house, and the quantity of oil as litres x 10^{-3} per house. Row 18 was omitted when the model was run with the 'buy oil' activity, and row 19 was omitted when the model was run with the 'buy coal' activity.

Rows 20-31 describe the labour restraints, where the supply of labour in each month was estimated at a total of 320 hours.

The supplies of all resources are shown, for each restraint row, in column 2.

Table D.1 Linear Programme Table

Columns 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Rows 1	G.M	-615	-615	-378	-378	-329	-283	-329	-283	-268	-231	-268	-268	-231	-231	-251	-218	-251	-251	-218	-218	-251
2	RHS	CSF	CIF	ØSF	ØIF	TAH1S1	TAH1S2	TAH2S1	TAH2S2	TBH1S1	TBH1S2	TBH2S1.X	TBH2S1.Y	TBH2S2.X	TBH2S2.Y	TCH1S1	TCH1S2	TCH2S1.X	TCH2S1.Y	TCH2S2.X	TCH2S2.Y	TCH3S1.X
3 H3.PRE	2 ≥	2	1	2	1																	
4 H3.PØST	2 ≥	2	1	2	1																	
5 H2.PRE	0 ≥	-2		-2				1	1				1		1							
6 H2.PØST	0 ≥	-2		-2				1	1										1		1	
7 H1.PRE	0 ≥		-1		-1	1	1			1	1	1		1								
8 H1.PØST	0 ≥		-1		-1	1	1									1	1	1		1		1
9 YLD.MAY	0 ≥									-1.110	-0.926	-0.416	-0.416	-0.348	-0.348							
10 YLD.JN	0 ≥									-1.332	-1.112	-1.667	-1.667	-1.392	-1.392							
11 YLD.JLY	0 ≥					-0.986	-0.824	-0.449	-0.375	-1.554	-1.297	-1.667	-1.667	-1.392	-1.392							
12 YLD.AUG	0 ≥					-1.48	-1.235	-1.347	-1.125	-0.444	-0.371	-0.416	-0.416	-0.348	-0.348							
13 YLD.SEPT	0 ≥					-1.973	-1.647	-1.796	-1.500													
14 YLD.OCT	0 ≥					-1.973	-1.647	-1.796	-1.500							-0.376	-0.314					
15 YLD.NØV	0 ≥					-1.480	-1.235	-1.796	-1.500							-2.258	-1.885	-0.360	-0.360	-0.301	-0.301	-0.324
16 YLD.DEC	0 ≥					-1.480	-1.235	-1.347	-1.125							-3.388	-2.827	-4.327	-4.327	-3.611	-3.611	-3.894
17 YLD.JAN	0 ≥					-0.493	-0.411	-0.449	-0.375							-1.505	-1.257	-2.524	-2.524	-2.107	-2.107	-2.271
18 QTY.CØAL	0 ≥					26.665	26.665	3.575	3.575	16.657	16.657	2.334	2.334	2.334	2.334	11.455	11.455	1.222	1.222	1.222	1.222	-
19 QTY.ØIL	0 ≥					13.34	13.34	1.788	1.788	8.335	8.335	1.166	1.166	1.166	1.166	5.730	5.730	0.611	0.611	0.611	0.611	-
20 LAB.JAN	320 ≥					72	60	70	59	-	-	-	-	-	-	122	103	152	152	129	129	145
21 LAB.FEB	320 ≥					-	-	-	-	73	63	73	73	63	63	-	-	-	-	-	-	-
22 LAB.MAR	320 ≥					-	-	-	-	51	44	51	51	44	44	-	-	-	-	-	-	-
23 LAB.APR	320 ≥					73	63	73	63	49	41	49	49	41	41	-	-	-	-	-	-	-
24 LAB.MAY	320 ≥					51	44	51	44	85	70	63	63	53	53	-	-	-	-	-	-	-
25 LAB.JUNE	320 ≥					49	41	49	41	105	91	112	112	100	100	-	-	-	-	-	-	-
26 LAB.JLY	320 ≥					82	61	65	48	111	97	112	112	100	100	-	-	-	-	-	-	-
27 LAB.AUG	320 ≥					110	95	105	91	58	61	56	56	60	60	73	63	73	73	63	63	73
28 LAB.SEPT	320 ≥					124	107	119	103	-	-	-	-	-	-	51	44	51	51	44	44	51
29 LAB.ØCT	320 ≥					124	107	119	103	-	-	-	-	-	-	60	50	49	49	41	41	49
30 LAB.NØV	320 ≥					110	95	119	103	-	-	-	-	-	-	126	106	70	70	58	58	68
31 LAB.DEC	320 ≥					110	95	105	91	-	-	-	-	-	-	167	142	194	194	166	166	182

Table D.1 - continued

Columns 1	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Rows 1	-251	-251	-218	-218	-218	1578	1578	1578	630	675	809	1168	1303	1486	862	593	638	α1	α2
2	TCH3S1.Y	TCH3S1.Z	TCH3S2.X	TCH3S2.Y	TCH3S2.Z	LETT.Z	LETT.Y	LETT.X	SEL.T.MY	SEL.T.JN	SEL.T.JL	SEL.T.AU	SEL.T.SE	SEL.T.OC	SEL.T.NO	SEL.T.DE	SEL.T.JA	BUY OIL	BUY COAL
3 H3.PRE						1													
4 H3.PØST		1			1														
5 H2.PRE							1												
6 H2.PØST	1			1															
7 H1.PRE								1											
8 H1.PØST			1																
9 YLD.MAY									1										
10 YLD.JN										1									
11 YLD.JLY											1								
12 YLD.AUG												1							
13 YLD.SEPT													1						
14 YLD.OCT														1					
15 YLD.NØV	-0.324	-0.324	-0.270	-0.270	-0.270										1				
16 YLD.DEC	-3.894	-3.894	-3.250	-3.250	-3.250											1			
17 YLD.JAN	-2.271	-2.271	-1.895	-1.895	-1.895												1		
18 QTY.CØAL	-	-	-	-	-														-1
19 QTY.ØIL	-	-	-	-	-													-1	
20 LAB.JAN	145	145	123	123	123	-	-	-											
21 LAB.FEB	-	-	-	-	-	18	18	18											
22 LAB.MAR	-	-	-	-	-	5	5	5											
23 LAB.APR	-	-	-	-	-	16	16	16											
24 LAB.MAY	-	-	-	-	-	14	14	14											
25 LAB.JUNE	-	-	-	-	-	2	2	2											
26 LAB.JLY	-	-	-	-	-	10	10	10											
27 LAB.AUG	73	73	63	63	63	9	9	9											
28 LAB.SEPT	51	51	44	44	44	-	-	-											
29 LAB.ØCT	49	49	41	41	41	-	-	-											
30 LAB.NØV	68	68	57	57	57	-	-	-											
31 LAB.DEC	182	182	155	155	155	-	-	-											