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APPLICATIONS OF LINEAR MODELLING  
IN ENERGY ANALYSIS

A thesis presented in partial fulfilment  
of the requirements for  
the Degree of Doctor of Philosophy  
in Technology at  
Massey University

MURRAY GRAHAM PATTERSON

1984

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## ABSTRACT

The primary objective of this study was to explore the use of classical linear models in Energy Analysis; so as to resolve some of the methodological problems associated with Energy Analysis, and to extend the scope and potential of Energy Analysis as a scientific discipline. This was undertaken in the form of two separate yet related discourses.

The first discourse provided a basis for resolving the energy quality problem encountered in Energy Analysis. A general equation was hypothesized and tested:

$$m_1 \sum_{i=1}^{i=j} (Y_1)_i + m_2 \sum_{i=1}^{i=j} (Y_2)_i + \dots m_n \sum_{i=1}^{i=j} (Y_n)_i \\ = n_1 \sum_{i=1}^{i=j} (X_1)_i + n_2 \sum_{i=1}^{i=j} (X_2)_i + \dots n_n \sum_{i=1}^{i=j} (X_n)_i$$

where:  $y$  = effective energy output of an end-use class ( $\Delta H$  output),  
known

$x$  = primary energy input ( $\Delta H$  input), known

$m$  = quality coefficient for an effective energy output (quality equivalents/  $\Delta H$  output), unknown

$n$  = quality coefficient for a primary energy input (quality equivalents/  $\Delta H$  input), unknown

$i$  = energy supply use pathways,  $j$  = number of pathways.

The matrix of simultaneous linear equations represented by this equation is usually overdetermined. Therefore, an appropriate solution method is a fitting procedure, such as regression. Further, in order to solve this general equation, one coefficient must arbitrarily be given a value equal to unity. Hence, all estimated coefficients are expressed in terms of multiples of that coefficient (termed quality equivalents).

The general equation was first tested for the 1976 New Zealand economy, so as to estimate 'actual' quality coefficients. Subsequently, the general equation was tested for a notional 'energy efficient' New Zealand economy, so as to estimate 'long run' quality coefficients, which reflected thermodynamic limits. Generally very accurate estimates of the coefficients were obtained. The solutions to the equations indicated that hydroelectricity was the highest quality

primary energy source, followed by natural gas, oil, coal and then wood.

The second discourse examined the 'optimal' use of primary energy resources in the New Zealand food system, using the formalism of Linear Programming. A preliminary discussion concluded that the concept of 'optimality' had greater potency than the concept of 'efficiency' in evaluating the use of energy resources, particularly in food systems. For each food sector (Production, Processing, Export-Import, Distribution, Catering and Household), coefficient matrices were assembled, drawing on literature data. Various combinations of constraints and objective functions were applied, in different Runs. The main objective functions used were minimising energy inputs for providing a nutritionally adequate diet, or maximising net energy gain from exporting agro-food products. The most critical constraints were found to be land area and market demand constraints.

Detailed results of the Linear Programming runs are presented and discussed. An energetically 'optimal' diet was found to consist of large amounts of cereals, significant amounts of fresh fruit and vegetables and dairy products, and a very small amount of meat. Such a diet provided the Recommended Daily Allowances, for all nutritional elements, for the New Zealand population. Meat, Fish and Dairy products were found to have a particularly important function as commodities to be traded for imports of oil and energy intensive goods.

A final discussion reviewed the use of Linear Models in Energy Analysis, and future directions for growth and development in Energy Analysis.

## PREFACE

This thesis is part of two research programmes being undertaken in the Food Technology Research Centre. The first research programme began in the early 1970's, and has attempted to introduce quantitative techniques (principally Linear Programming and Extensions) to product development and diet planning. This has resulted in a number of PhD dissertations (Edwardson, 1974; Anderson, 1975; Chittaporn, 1977; Ngarmsak, 1983). The second research programme was initiated in 1977, and has attempted to quantify energy use in the food system, and to identify energy conservation measures particularly applicable to the food processing sector. This research has been funded by the New Zealand Energy Research and Development Committee. The material for this thesis has been drawn from the findings of Contract 3123 "Energy Requirements for Food Supply in New Zealand".

Much of the details of surveys undertaken for Contract 3123 and used in this thesis have been published by the N.Z.E.R.D.C., under the author's name. Readers are recommended to refer to these reports for further details:

- (1) Patterson, M.G. and Earle, M.D. 1982. Energy Use in the Catering Industry. N.Z.E.R.D.C. Report P66. (Appendix F).
- (2) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of Shopping for Food. N.Z.E.R.D.C. Report P67. (Appendix G).
- (3) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of the Wholesale Distribution of Foods. N.Z.E.R.D.C. Report P68. (Appendix H).
- (4) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of the Household Preparation and Storage of Foods. N.Z.E.R.D.C. Report P69. (Appendix I).
- (5) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of Food Retailing. N.Z.E.R.D.C. Report P70. (Appendix J).
- (6) Patterson, M.G. and Earle, M.D. 1984. Energy Use in the New Zealand Food System. N.Z.E.R.D.C. Report (In Press).

Another paper that summarises much of Part A of this thesis, has also been published: Patterson, M.G. 1983. Estimation of the Quality of Energy Sources and Uses. Energy Policy 11:4 346-359 (this paper appears in Appendix A).

## ACKNOWLEDGEMENTS

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contract, formed the basis of this thesis. I therefore wish to thank the NZERDC for providing me with the opportunity to undertake this research, and subsequently use it as the basis for this thesis.

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## TABLE OF CONTENTS

ABSTRACT	i
PREFACE	ii
ACKNOWLEDGEMENTS	iv
1. INTRODUCTION	1
1.1 Objectives and Approach	1
1.2 Background	1
1.2.1 Energy Analysis and its Development	1
1.2.1.1 Definition	1
1.2.1.2 History and Origins of Energy Analysis	2
1.2.1.3 Methodological Approaches	4
1.2.1.4 Methodological Problems	5
1.2.1.5 Uses and Applications	8
1.2.2 Linear Modelling in Energy Analysis and Economics	9
1.2.2.1 Definition of Linear Models	9
1.2.2.2 Typology of Linear Models in Economics	10
1.2.2.3 Uses and Applications of Linear Models in Energy Analysis	13
PART A: A LINEAR REGRESSION APPROACH TO ENERGY QUALITY	
2. METHODOLOGY	15
2.1 Introduction	15
2.1.1 Problem of Energy Quality in Energy Analysis	15

2.1.2	Previous Approaches to Energy Quality in Energy Analysis	15
2.1.3	Reiteration and Statment of Objective for Part A	17
2.2	Proposed Methodology to Solve the Energy Quality Problem	17
2.2.1	Definitions	17
2.2.2	Energy Accounting Procedures	18
2.2.3	Regression Equations and Solutions	18
2.2.4	Statistical Analysis of Solutions	20
2.2.5	Recommended Methods of Model Selection and Improvement	21
2.2.6	Central Hypothesis and Model Building	22
2.2.7	Post Regression Analysis of Pathways	23
2.3	Conclusion	24
3.	AN APPLICATION TO THE NEW ZEALAND ECONOMY, 1976	25
3.1	Data Sources	25
3.2	Inputs and Outputs Considered	25
3.3	Pathways Considered	26
3.4	Data Set and Regression Equations	27
3.5	Computer Analysis of Data Set	30
3.6	Statistical Analysis of Solutions to the Regression Equations	31
3.6.1	Detailed Results	32
3.6.2	An Example of Computer Print Out for Model $n_1 = 1$	36
3.6.3	Interpretation of Results	37
3.6.3.1	t Ratios	37
3.6.3.2	F Ratios	38
3.6.4	Model Selection and Improvement	39
3.7	Post Regression Analysis of Pathways, for $m_6$ Model	39
3.7.1	Residuals of Pathways (Relative Net Energy Yields)	40
3.7.2	Relative Efficiency of Pathways	43
3.8	Central Hypothesis: Relationship Between Quality of Inputs, Quality of Outputs and Enthalpic Efficiency	44
3.9	Discussion	44
3.9.1	Adequateness of the Models and Modelling	

Procedure	44
3.9.2 Energy Efficiency and Technological Development	47
3.9.2.1 Evidence	47
3.9.2.2 Interpretation	47
3.9.3 Conclusion	49
4. AN APPLICATION TO AN ENERGY EFFICIENT ECONOMY -	50
4.1 Introduction	50
4.2 Data Sources	50
4.3 Inputs and Outputs Considered	50
4.4 Pathways Considered	51
4.5 Data Set and Regression Equations	53
4.6 Statistical Analysis of Solutions to the Regression Equations	53
4.6.1 Detailed Results (Unweighted Models)	57
4.6.2 Interpretation of Results (Unweighted Models)	61
4.6.2.1 Estimates of Coefficients and t Ratios	61
4.6.2.2 F Ratios	61
4.6.3 Detailed Results (Weighted Models)	62
4.6.4 Interpretation of Results (Weighted Models)	67
4.6.4.1 Estimates of Coefficients and t Ratios	67
4.6.4.2 F Ratios	67
4.6.5 Model Selection and Improvement	68
4.7 Post Regression Analysis of Pathways, for $m_2$ Model	71
4.7.1 Residuals of Pathways (Relative Net Energy Yields)	71
4.7.2 Relative Efficiency of Pathways	75
4.8 Central Hypothesis: Relationship Between Quality of Inputs, Quality of Outputs and Enthalpic Efficiency	76
4.9 Linear Programming Extensions	79
4.9.1 Introduction	79
4.9.2 Formulation of the Model	79
4.9.2.1 Notations	79
4.9.2.2 Objective function(s)	79
4.9.2.3 Constraints	79
4.9.3 Some Preliminary Runs	82
4.9.3.1 Run 1 (Minimisation of IQ)	82
4.9.3.2 Run 2 (Minimisation of IQ non-renewable)	82

4.9.4	Some Improvements and Extensions	85
4.9.4.1	Objective(s)	85
4.9.4.2	Constraints	86
4.9.4.3	Substitution Possibilities and Interdependence Equations	87
4.9.4.4	Inclusion of Future Supply and Use Options	81
4.9.4.5	Post-Optimal Sensitivity Analysis	87
5.	DISCUSSION	88
5.1	Uses and Applications of Data Derived from the Modelling Procedure	88
5.1.1	Net Energy Analysis	88
5.1.2	Technology and Process Assessment, and End-Use Matching	89
5.1.3	Policy Making and Formulation	90
5.1.4	Energy Statistics	91
5.2	Possible Extensions of Modelling Procedure Relevant to Energy Analysis and Theories of Production	91
5.3	Evaluation of the Modelling Procedure for Solving the Energy Quality Problem	94
5.4	Further Uses of Regression Analysis in Energy Analysis	96
5.5	Conclusions	98

PART B: LINEAR PROGRAMMING MODELLING OF ENERGY USE IN THE  
NEW ZEALAND FOOD SYSTEM

6.	INTRODUCTION AND METHODOLOGY	99
6.1	Introduction and Literature Review	99
6.1.1	Previous Energy Analyses of Food Supply	99
6.1.2	Previous Optimisation Models of Food Supply-Use Studies	102
6.1.3	Critical Review of Previous Studies	103
6.1.3.1	Concepts of Energy Efficiency	103

6.1.3.2	Concepts of Optimality	104
6.1.3.3	Numeraire and Energy Analysis	104
6.1.4	Net Energy Concept	107
6.1.5	Reiteration and Statement of Objective for Part B	108
6.2	Methodology: Data Collection and Analysis	108
6.2.1	Classification of Sectors	108
6.2.2	Classification of Inputs and Outputs	108
6.2.2.1	Exogenous Inputs	110
6.2.2.2	Exogenous Outputs	111
6.2.2.3	Endogenous Inputs and Outputs	111
6.2.3	Estimation of Energy Inputs	111
6.2.3.1	Primary Energy Inputs Considered	112
6.2.3.2	Production Sector	113
6.2.3.3	Processing Sector	114
6.2.3.4	Export-Import Sector	115
6.2.3.5	Wholesale Distribution Sector	115
6.2.3.6	Retail Storage	116
6.2.3.7	Shopping	117
6.2.3.8	Household Preparation and Storage	118
6.2.3.9	Household Production	119
6.2.3.10	Catering	120
6.2.3.11	Hotels	121
6.2.4	Estimation of Other Inputs and Outputs	121
6.2.4.1	Direct Land Inputs	121
6.2.4.2	Direct Labour Inputs	122
6.2.4.3	Food Imports and Exports	123
6.2.4.4	Nutritional Outputs	123
6.2.4.5	Endogenous Inputs and Outputs	123
6.3	Methodology: Linear Programming	124
6.3.1	Introduction	124
6.3.1.1	Linearity Assumption	125
6.3.1.2	Interdependencies Between Sectors, and Input-Output Analysis	125
6.3.1.3	Solution of Linear Programming Models and Other Sets of Linear Equations	127
6.3.2	Coefficient Matrix	128
6.3.2.1	Formulation	128
6.3.2.2	MPS Format	129
6.3.2.3	Units of Coefficient	130
6.3.2.4	Scaling of Coefficients	130





and Codings	197
8.2.4.2 Allowances for Wastes and Loss of Nutrients	198
8.2.4.3 Nutritional Requirements of the New Zealand Population	200
8.2.5 Matrix Formulation	202
8.3 Catering-Hotel Sector Matrix	204
8.3.1 Introduction	204
8.3.2 Energy Inputs	205
8.3.2.1 Catering Industry	205
8.3.2.2 Hotel Industry	209
8.3.3 Labour Inputs	211
8.3.4 Endogenous Inputs and Outputs	211
8.3.4.1 Catering Industry	211
8.3.4.2 Hotel Industry	213
8.3.5 Nutritional Outputs	214
8.3.6 Matrix Formulation	214
9. PRELIMINARY RESULTS AND DISCUSSION	216
9.1 Introduction	216
9.2 Run 1: Standard Run	216
9.2.1 Introduction	216
9.2.2 Objective Function	217
9.2.3 Constraints	217
9.2.4 Results	217
9.2.4.1 Objective Function and Total Energy Requirements	217
9.2.4.2 Export Earnings	219
9.2.4.3 Direct Labour Requirements	221
9.2.4.4 Direct Land Requirements	221
9.2.4.5 Product Mixes and Structure of the Food System	221
9.2.4.6 Nutritional Outputs	221
9.3 Run 2: Minimisation of Q	222
9.3.1 Introduction	222
9.3.2 Objective Function	223
9.3.3 Constraints	223
9.3.3.1 Nutritional Requirements	223
9.3.3.2 Land Constraints	224

9.3.3.3	Export-Import Constraints	225
9.3.3.4	Other Constraints	
9.3.4	Results	225
9.3.4.1	Objective Function and Total Energy Requirements	225
9.3.4.2	Optimal Diet	227
9.3.4.3	Nutritional Outputs	229
9.3.4.4	Exports-Imports	232
9.3.4.5	Direct Labour Requirements	233
9.3.4.6	Direct Land Requirements	233
9.3.4.7	Structure of the Food System	233
9.4	Run 3: Maximisation of Q (Net Energy Yield)	235
9.4.1	Introduction	235
9.4.2	Objective Function	236
9.4.3	Constraints	236
9.4.3.1	Domestic Food Consumption Constraints	236
9.4.3.2	Land Constraints	236
9.4.3.3	Export-Import Constraints	237
9.4.3.4	Other Constraints	237
9.4.4	Results	237
9.4.4.1	Objective Functions and Total Energy Requirements	237
9.4.4.2	Export Earnings	237
9.4.4.3	Direct Labour Requirements	240
9.4.4.4	Direct Land Requirements	240
9.4.4.5	Structure of Food System	240
9.4.4.6	Household Sector	242
9.4.4.7	Nutritional Outputs	244
9.5	Run 4: Maximisation of Net Export Earnings	244
9.5.1	Introduction	244
9.5.2	Objective Function	244
9.5.3	Constraints	244
9.5.3.1	Nutritional Requirements	244
9.5.3.2	Land Constraints	243
9.5.3.3	Export-Input Constraints	245
9.5.3.4	Other Constraints	245
9.5.4	Results	245
9.5.4.1	Objective Function and Export Earnings	245
9.5.4.2	Total Energy Requirement and Net	

Energy Yield	247
9.5.4.3 Direct Labour Requirements	247
9.5.4.4 Direct Land Requirements	247
9.5.4.5 Structure of Food System	249
9.5.4.6 Nutritional Outputs	251
9.6 Discussion	251
9.6.1 Review of the Main Empirical Results and Implications	251
9.6.2 Efficiency and Optimality	254
9.6.3 Limitations and Problems	254
9.6.3.1 Practical Computational Problems	254
9.6.3.2 Fixed Proportionality Assumption	256
9.6.3.3 Changes of Physical Coefficients Over Time, with Improved Technology	257
9.6.3.4 Changes in Economic Coefficients and Constraints, Over Time	259
9.6.3.5 Conclusion	260
9.6.4 Extensions and Improvements of Coefficient Matrices	260
9.6.5 Uses of the Linear Programming Model of the New Zealand Food System	261
9.6.5.1 Long Term Planning Model	261
9.6.5.2 Other Uses and Short Term Planning	261
9.6.6 Final Evaluation of the Linear Programming Model of the New Zealand Food System	263
10. FINAL REVIEW AND DISCUSSION	264
10.1 Mathematical and Linear Modelling in Energy Analysis	264
10.1.1 Nature of Mathematical Models	264
10.1.2 Linear Modelling in Energy Analysis	265
10.1.3 Review of Linear Modelling Applications in this Study	266
10.1.4 Further Applications of Mathematical and Linear Modelling in Energy Analysis	267
10.2 Further Developments of Energy Analysis	268
10.2.1 Resolution of Methodological Problems	269
10.2.2 Resolution of Methodological Problems Associated with Energy Coefficients	269
10.2.2.1 Assumptions Underpinning Energy	

Coefficients	269
10.2.2.2 Towards a Production Function, Based on Physical Inputs	271
10.2.2.3 Towards an Entropic Theory of Production, Based on Thermodynamics	272
10.2.3 Economics and Energy Analysis Reconsidered	273
10.3 Conclusions	274

#### REFERENCES CITED

#### APPENDICES

- A. Estimations of the Quality of Energy Sources and Uses (Copy of a paper published in the journal Energy Policy 11:4 346-359).
- B. Energy Use Pathways for the New Zealand Economy, 1976: Data Sources and Calculations. (Microfiche).
- C. Energy Use Pathways for the Energy Efficient New Zealand Economy: Data Sources and Calculations. (Microfiche)
- D. MPS Format Input for the General and Distribution Models, of the Linear Programming Model of Energy Use in the New Zealand Food System. (Microfiche)
- E. Codes Used for the MPS Input for the General and Distribution Models, of the Linear Programming Model of Energy Use in the New Zealand Food System. (Microfiche)
- F. Energy Use in the Catering Industry (Copy of New Zealand Energy Research and Development Committee Report P66) (Microfiche).
- G. Total Energy Requirements of Shopping for Food (Copy of New Zealand Energy Research and Development Committee Report P67) (Microfiche).
- H. Total Energy Requirements of the Wholesale Distribution Foods

(Copy of New Zealand Energy Research and Development  
Committee Report P68) (Microfiche).

- I. Total Energy Requirements of the Household Preparation and  
Storage of Foods (Copy of New Zealand Energy Research and  
Development Committee Report P69) (Microfiche).
  
- J. Total Energy Requirements of Food Retailing (Copy of New Zealand  
Energy Research and Development Committee Report P70)  
(Microfiche).

## LIST OF TABLES

	<u>PAGE</u>
3.1 Actual New Zealand Energy Economy: Technologies and Operational Efficiencies	28
3.2 Data Set: Gross Energy Requirements of Energy Supply-Use Pathways in the New Zealand Energy Economy, 1976	29
3.3 Analysis of Residuals, for Cooking Equivalents ( $m_6$ ) for the New Zealand Economy, 1976	41
3.4 Numerical Calculations for Pathways of the $n_1(m_6)$ Model of the New Zealand Economy, 1976	42
4.1 An Energy Efficient New Zealand Economy: Assumed Technologies and Operational Efficiencies	54
4.2 Data Set: Gross Energy Requirements of Energy Supply-Use Pathways in an Energy Efficient New Zealand Economy	55
4.3 Comparison of F Ratios for Weighted and Unweighted Models of an Energy Efficient Economy	69
4.4 Comparison of Estimates of Coefficients Standardised so $n_1=1$ , and F Ratios for Models ( $n_1-n_7$ , $m_1-m_7$ ) of an Energy Efficient Economy (Unweighted)	70
4.5 Analysis of Residuals for High Grade Transport Equivalents ( $m_2=1$ ) for an Energy Efficient Economy	72
4.6 Numerical Calculations for Pathways of the $n_1(m_2)$ Model of an Energy Efficient Economy	73
4.7 Solution of Linear Programming Run 1 (Minimisation of IQ)	83
4.8 Solution of Linear Programming Run 2 (Minimisation of IQ-non-renewable)	84

LIST OF TABLES - continued

	<u>PAGE</u>
5.1 Comparison of Energy Consumption Statistics for New Zealand (1981), Expressed in Enthalpy and Quality Equivalent Terms	92
6.1 Energy Requirements of Selected National Food Systems	101
6.2 Survey Classification and the New Zealand Standard Industrial Classification	109
7.1 Calculation of a Hydro-Electricity Equivalent ( $n_1(m_2)$ ): Primary Energy Input ( $\Delta H$ ) Ratio, for the New Zealand Economy	142
7.2 Energy Transformation Matrix, for the New Zealand Food System Model (1978-79)	145
7.3 Total Energy Requirements (TJ/yr) of the Production Sector of the Food System in New Zealand	149
7.4 Land Requirements (000ha) and Energy Intensities (GJ/yr/ha) for the Production Sectors of the New Zealand Food System	151
7.5 Definition of Land Use Capability Classes	153
7.6 Assumed Classes of Land Suitable for Various Production Sectors	155
7.7 Land Class Availability for Agricultural and Horticultural Production	157
7.8 Matrix for Land Inputs into the Production Sectors for the New Zealand Food System Model (1978-79)	158
7.9 Direct Labour Requirements (Full-time Equivalent man-years/yr) and Labour Intensity (Full-time Equivalent man-years/yr/(000ha)) for Production Sectors in the New Zealand Food System	160

LIST OF TABLES - continued

	<u>PAGE</u>
7.10 Production Sector Matrix, for New Zealand Food System Model (1978-79)	164
7.11 Codings and New Zealand Standard Industrial Classifications for Processing Sectors	165
7.12 Total Energy Requirements (TJ/yr) of the Processing Sectors of the Food System in New Zealand	168
7.13 Direct Labour Requirements (Full-time Person Equivalent/yr) for the Food Processing Sector of the New Zealand Food System, 1978-79	169
7.14 Processing Sector Matrix, for New Zealand Food System Model (1978-79)	171
7.15 Export-Import Sector Matrix for the New Zealand Food System Model (1978-79)	177
8.1 Total Energy Requirements (TJ/yr) of the Wholesale Distribution Sector of the Food System, in New Zealand	180
8.2 Total Energy Intensities (MJ/kg) for Storage Steps in the Wholesale Distribution of Foods, in New Zealand	182
8.3 Total Energy Intensities (MJ/kg) for Transport Steps in the Wholesale Distribution of Food in New Zealand	183
8.4 Total Energy Requirements (TJ/yr) of the Retail Storage Steps in the N.Z. Food System, 1981-82	185
8.5 Total Energy Intensities (MJ/kg) of the Retail Storage Steps in the New Zealand Food System, 1981-82	186
8.6 Total Energy Requirements (TJ/yr) of the Shopping for Food in New Zealand, 1981-82	189
8.7 Total Energy Intensities (MJ/kg) for the Shopping Steps in the New Zealand Food System, 1981-82	189

LIST OF TABLES - continued

	<u>PAGE</u>	
8.8	Distribution-Transport Sector Matrix for the New Zealand Food System Model (1978-79)	191
8.9	Total Energy Requirements (TJ/yr) of the Household Preparation and Storage Sector of the Food System	194
8.10	Total Energy Intensities (MJ/kg) for the Household Preparation, Storage and Production of Foods, 1980-81	196
8.11	Total Household Food Production (Tonnes/yr)	196
8.12	Vitamin Losses During Household Cooking	199
8.13	Minimum Nutritional Requirements of the New Zealand Population (1978-79)	201
8.14	Household Sector Matrix for the New Zealand Food System Model (1978-79)	203
8.15	Direct Energy Intensities (MJ/kg) for 33 Catering Establishments in Palmerston North, Estimated by Multiple Linear Regression	207
8.16	Total Energy Requirements (TJ/yr) of the Catering Industry 1980-82	208
8.17	Total Energy Requirements (TJ/yr) of the Hotel Industry, 1980-81 - 1981-82	210
8.18	Foodstuffs Used by 33 Catering Establishments in Palmerston North (kg/weeks)	212
8.19	Catering - Hotels Sector Matrix for the New Zealand Food System Model (1978-79)	215
9.1	Primary Energy Requirements of Run 1 - General Model	218
9.2	Primary Energy Requirements of Run 1 and 3 - Distribution Model	218

LIST OF TABLES - continued

	<u>PAGE</u>	
9.3	Total Energy Requirements of N.Z. Economy, 1978-79	220
9.4	Primary Energy Requirements of Run2 - General Model	226
9.5	Primary Energy Requirements of Run 2 - Distribution Model	226
9.6	Optimal Diet Solution for Run2 - General Model	228
9.7	Nutritional Outputs for Run 2 - General Model	230
9.8	Sources of Nutritional Output for Run 2 - General Model	231
9.9	Direct Land Requirements (000ha) for Run 2 - General Model	234
9.10	Food System Structure for Run 2 - General Model	234
9.11	Primary Energy Requirements of Run 3 - General Model	239
9.12	Exports for Run 3 - General Model	241
9.13	Direct Land Requirements (000ha) of Run 3 - General Model	241
9.14	Household Cooking, Food Preparation and Storage Modes for Run 3 - General Model	243
9.15	Exports for Run 4 - General Model	246
9.16	Primary Energy Requirements of Run 4 - General Model	248
9.17	Primary Energy Requirements of Run 4 - Distribution Model	248
9.18	Direct Land Requirements for Run 4 - General Model	250
9.19	Nutritional Outputs for Run 4 - General Model	250
9.20	Energy Ratios for Various Runs of the New Zealand Food System Model	255

LIST OF FIGURES

	<u>PAGE</u>
3.1 Residual Plot: Standardised Residual vs Pathways for $m_6$ Model of New Zealand Economy, 1976	40
3.2 Quality of Inputs vs Enthalpic Efficiency for Pathways 1-4, $n_1$ Model of New Zealand Economy, 1976	45
3.3 Quality of Inputs vs Enthalpic Efficiency for Pathway 5, $n_1$ Model of New Zealand Economy, 1976	45
3.4 Quality of Inputs vs Enthalpic Efficiency for Pathways 6-13, $n_1$ Model of New Zealand Economy, 1976	45
3.5 Quality of Inputs vs Enthalpic Efficiency for Pathways 14-17, $n_1$ Model of New Zealand Economy, 1976	45
3.6 Quality of Inputs vs Enthalpic Efficiency for Pathways 18-26, $n_1$ Model of New Zealand Economy, 1976	46
3.7 Quality of Inputs vs Enthalpic Efficiency for Pathways 27-31, $n_1$ Model of New Zealand Economy, 1976	46
3.8 Energy Requirements for the Production of Ammonia	48
3.9 Process Energy Requirement for the Production of Pig Iron	48
3.10 Process Energy Requirements vs Technological Development Through time: A Generalised Model	48
4.1 Residual Plot: Standardised Residual vs Pathways for $m_2$ Model of an Energy Efficient Economy	74
4.2 Quality of Inputs vs Enthalpic Efficiency of Pathways 1-5, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	77

LIST OF FIGURES - continued

	<u>PAGE</u>
4.3 Quality of Inputs vs Enthalpic Efficiency of Pathways 6-10, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	77
4.4 Quality of Inputs vs Enthalpic Efficiency of Pathways 14-18, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	77
4.5 Quality of Inputs vs Enthalpic Efficiency of Pathways 11-13, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	77
4.6 Quality of Inputs vs Enthalpic Efficiency of Pathways 19-23, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	78
4.7 Quality of Inputs vs Enthalpic Efficiency of Pathways 24-28, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	78
4.8 Quality of Inputs vs Enthalpic Efficiency of Pathways 29-33, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy	78
6.1 Schematic Relationship Between Energy Requirements (MJ/kg) of Materials and Ore Grade	106
7.1 Land Use Suitability of Class I-VII Land	152
9.1 Schematic Isoquant Curves for Energy-Labour Inputs with Improved Technology-Management, where $T_1, T_2, T_3$ represent Time Periods approaching $T_n$ .	258
10.1 Schematic Isoquant for the Labour-Land Trade-Off	270
10.2 Schematic Isoquant for the Labour-Energy Trade-Off	270
10.3 Schematic Isoquant for the Land-Energy Trade-Off	270
10.4 Schematic Isoquant for the Labour-Time Trade-Off	270
10.5 Schematic Isoquant for the Energy-Time Trade-Off	270
10.6 Schematic Isoquant for the Land-Time Trade-Off	270