THE SANDWICH ALGORITHM FOR SPATIAL EQUILIBRIUM ANALYSIS

by

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CONTENTS

LIST OF FIGURES

PREFACE

Mathematical models have proved very useful over many years in explaining the organisation of farm supply, transport and processing facilities for a range of commodities including wheat. This paper explores the usefulness of a recently developed algorithm which offers the prospect of dealing with some complex transport and pricing issues which have proved difficult to handle in the past.

The authors demonstrate that this class of techniques will enable analysts to incorporate farm supply response, lumpy transport and handling facilities and pricing mechanisms simultaneously in the future.

R.G. Lattimore
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SECTION 1

INTRODUCTION

Recent advances in mathematical programming techniques have made it possible to provide more realistic solutions to applied economic problems. Although mathematical programming techniques are widely used, the economic content of the solutions is often limited by the assumptions imposed by the algorithms available. This report is designed to demonstrate the increased flexibility which is currently available for the solution of a wide range of spatial economic problems.

Transportation and transhipment models have been widely used in the analysis of the impact of policy changes on spatial activity, Borrell & Zwart [1]; Beck, Rathbun and Abbott [2]. One of the major shortcomings of such models has been an inability to model the impact of more flexible pricing policies on regional supply and demand, while maintaining the realistic non-linearities which are associated with processing and transportation costs. In this paper a simplified version of the transhipment model developed by Borrell & Zwart [1] is modified to incorporate regional supply response while at the same time retaining complex processing and handling cost relationships.

This report outlines the general form of the spatial equilibrium problem and some of the solution techniques available, in a format easily understood by readers not conversant with operational research techniques. Initially the problem is defined and solution methods used in the past are then briefly described. The advantages and disadvantages of these methods are outlined before showing how a relatively new solution technique may be able to improve both the scope and flexibility of the problems being solved.

1.1 Description of the General Spatial Equilibrium Problem

The general form of a spatial equilibrium problem consists of separated supply and demand points (markets or trading sites) for one or more goods. Supply points may or may not be demand points and vice versa. The quantity supplied or demanded of a particular good, at each trading site, is dependent upon the price of that good. For such a system to be in a state of economic equilibrium, the total quantity supplied and demanded of each good at each trading site, must be equal. In addition, for price stability the price of a good at a demand point must not be less than the sum of the price at the original supply point and transport costs. This transport cost may also include intermediate processing between the source and destination point. Economic equilibrium is reached via the price mechanism.

Problems involving spatial equilibrium are usually characterised by one or more of the following:-

(1) Supplies and demands, at market sites, which are functions of the price offered or paid;

(2) Transportation and processing costs which are normally dependent upon the quantity transported or shipped. The price and quantity supplied of transport may also be dependent upon the level of total transportative activity.

(3) Cross elasticities of supply and demand between goods. This factor is particularly relevant to the multi-commodity spatial problem.

The range of problems applicable to spatial analysis include inter-regional trade, international trade, regional transport and facility location problems. In fact, most situations concerned with production and/or movement of goods in response to demand between discrete trading sites, can be formulated in the framework of spatial analysis.

1.2 Solution Methodology Used in the Past

The extent to which mathematical models can be used to approximate reality is invariably limited by model types available. Spatial equilibrium modelling is no exception. The linear transportation model formulated by Hitchcock [3] is well known as one of the first approaches to this type of problem. Demands and supplies are assumed to be known and fixed at each trading site, with the resultant solution determining the flows of goods between sites and their prices at each site. Many other formulations of spatial equilibrium problems, usually incorporating some degree of non-linearity, have since been used with varying success, most notably Quadratic Programming (QP) (Takayama [4,5]) and the Linear Complementary Problem (LCP) (Takayama [5,6]).

Spatial equilibrium modelling invariably requires 'implausible' assumptions about the real world whether it be fixity of supply and demand as in the transportation model, linear supply and demand functions, as in quadratic programming formulation, or that transportation and production processes are linear homogeneous with degree 1 and additive (i.e. scale factors absent). The basic problem is that many formulations of spatial problems require modelling a non-linear world using linear or quadratic models. Although it is possible to formulate and evaluate general non-linear programs, there can be major execution problems and the time involved in obtaining a global solution may be prohibitive.

SECTION 2

THE SANDWICH ALGORITHM

The 'Sandwich Algorithm', developed by Mackinnon [7,8,9,10] was used to demonstrate how relatively new solution techniques may be used to increase the scope and flexibility of spatial equilibrium analysis. The approach taken was to model, using the Sandwich Algorithm, a reduced version of the New Zealand wheat industry problem, previously solved using standard linear programming methods (Borrell & Zwart [1]).

The Algorithm was programmed in Fortran 77 and run on a VAX 11/780 (Lincoln College).

This section briefly outlines the main features of the algorithm without delving into the mathematics or theory involved. For a more rigorous presentation and description of the algorithm see MacKinnon [7,8,9,10].

2.1 Features of the Sandwich Algorithm

The main features, regarding the use of the Sandwich Algorithm to solve spatial problems are:

(1) The algorithm is capable of handling demand and supply curves which are linear, non-linear or even semi-smooth;

(2) Multi-commodity problems can be readily solved. The cross price effect inherent in such problems can also be captured in the specification of the demand and supply curves;

(3) Transport and processing costs can be included in a form which allows them to be dependent upon the quantity of throughput;

(4) Transport costs can be included as either endogeneous or exogenous to the system being modelled;

(5) Problem features such as flow bounds, ad valorem tariffs and differing exchange rates are also readily handled by the algorithm.

For a complete description of both the algorithm and its capabilities refer MacKinnon [10].

SECTION 3

DEMONSTRATION OF THE CAPABILITIES OF THE SANDWICH ALGORITHM

3.1 Introduction

The problem modelled was a reduced version of the New Zealand wheat industry problem (Borrell & Zwart [1]). Prior to using the Sandwich Algorithm, the problem was formulated as a linear transportation system and solved using standard linear programming techniques. This solution provided a 'benchmark with which results from the Sandwich Algorithm could be compared. To demonstrate the capabilities of the Sandwich Algorithm the problem was initially formulated as a transhipment model with non-linear supply functions and solved. Additional complexities were then added in a stepwise manner which facilitated a comparison of results of each formulation at each stage of the analysis. Five different formulations were solved using the algorithm.

3.2 Sample Problem Description

The essential components of this example were wheat production, conversion of wheat to flour, and transportation of both wheat and flour to regions of demand. The objective was to determine stable market clearing prices at all source (supply), intermediate (processing and shipping), and destination (demand) points, with all transfers occurring efficiently. Production, milling, transportation and port and shipping activities were included in the formulation. The activities are specified as follows:-

S1	South Island wheat supply region 1.
S2	South Island wheat supply region 2.
S3	North Island wheat supply.
M1,M2	South Island mills.
M3,M4	North Island mills.
D1	South Island flour demand region 1.
D2	South Island flour demand region 2.
D3	North Island flour demand region 1.
D4	North Island flour demand region 2.
P1,P2	South Island ports.
P3,P4	North Island ports.
S	The shipping activity between ports.

The initial transportation tableau is shown in Figure 1. This

FIGURE 1

Initial Transportation Tableau ($/tonne)

Sources \ Destinations		South Island Mills		North Island Mills		South Island Ports			North Island Ports		Final Demands for Flour			
		M1	M2	M3	M4	P1	P2	S	P3	P4	D1	D2	D3	D4
Wheat Supply	S1	5	36	62	88	10	40	∞	∞	∞	∞	∞	∞	∞
	S2	26	6	40	66	40	5	∞	∞	∞	∞	∞	∞	∞
	S3	100	100	6	30	∞	∞	∞	∞	∞	∞	∞	∞	∞
Mills Flour Supply	M1	0	∞	∞	∞	∞	∞	∞	∞	∞	18	51	81	108
	M2	∞	0	∞	∞	∞	∞	∞	∞	∞	55	18	58	82
	M3	∞	∞	0	∞	∞	∞	∞	∞	∞	98	68	18	53
	M4	∞	∞	∞	0	∞	∞	∞	∞	∞	118	88	53	18
South Island Ports	P1	∞	∞	∞	∞	0	∞	5	∞	∞	∞	∞	∞	∞
	P2	∞	∞	∞	∞	∞	0	5	∞	∞	∞	∞	∞	∞
Shipping	S	∞	∞	∞	∞	∞	∞	0	18	18	∞	∞	∞	∞
North Island Ports	P3	∞	∞	2	35	∞	∞	∞	0	∞	∞	∞	∞	∞
	P4	∞	∞	35	2	∞	∞	∞	∞	0	∞	∞	∞	∞

matrix was altered as further complexity was added to the formulation.

3.3 The Sample Problem Formulated as a Linear Transportation Model

The sample problem was formulated and solved as a linear transportation model. This was done to provide a convenient reference point with which solutions using other formulations and solution techniques could be compared. The transportation tableau ($/tonne) for this formulation is shown in Figure 1. Supplies ('000s of tonnes) were estimated for the source regions as follows:-

(1) South Island supply region 1 (S1)
S1 = 86

(2) South Island supply region 2 (S2)
S2 = 184

(3) South Island supply region 3 (S3)
S3 = 17

The final demands ('000s of tonnes) were estimated for the demand regions as follows:-

(1) South Island demand region 1 (D1)
D1 = 26

(2) South Island demand region 2 (D2)
D2 = 51

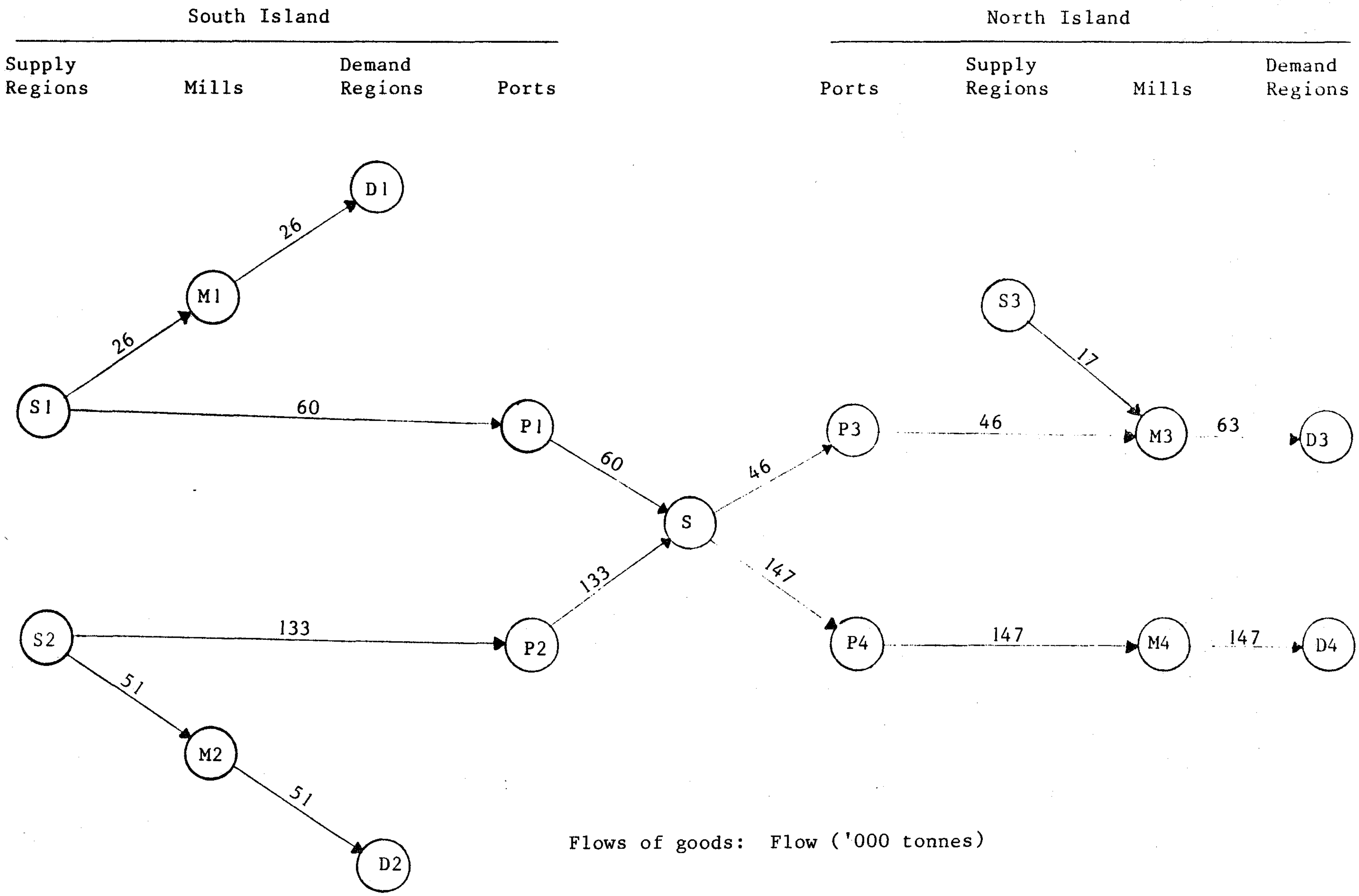
(3) North Island demand region 1 (D3)
D3 = 63

(4) North Island demand region 2 (D4)
D4 = 147

Results for this formulation are presented diagramatically in Figure 2. All transport costs, demands and supplies are constants.

FIGURE 2

Diagrammatic Results for the Linear Transportation Model



Flows of goods: Flow ('000 tonnes)

SECTION 4

RESULTS

4.1 Model I

In a competitive production situation such as exists in the New Zealand wheat industry, production is not static, but will respond to changes in prices received by producers. In a policy environment where prices in individual regions are changed to reflect changing transportation costs or policies, there will be a production response which may have significant regional implications.

In this version of the model, the supply response is assumed to be linear, and the particular functions used were derived from the elasticity data presented in Rich & Zwart [11].

The problem was formulated as a transhipment model with non-linear supply functions. The transportation tableau ($/tonne) is shown in Figure 1. Supply functions ('000s of tonnes) estimated for the source regions were as follows:-

(1) South Island supply region 1 (S1).
$S1 = 34.30 + .235\ P1$
P1 is the price/tonne offered to suppliers in S1

(2) South Island supply region 2 (S2).
$S2 = 18.34 + .753\ P2$
P2 is the price/tonne offered to suppliers in S2

(3) North Island supply region (S3).
$S3 = 3.36 + .062\ P3$
P3 is the price/tonne offered to suppliers in S3

The final demands ('000s of tonnes) were assumed to be perfectly inelastic and were as follows:-

(1) South Island demand region 1 (D1)
$D1 = 26$

(2) South Island demand region 2 (D2)
$D2 = 51$

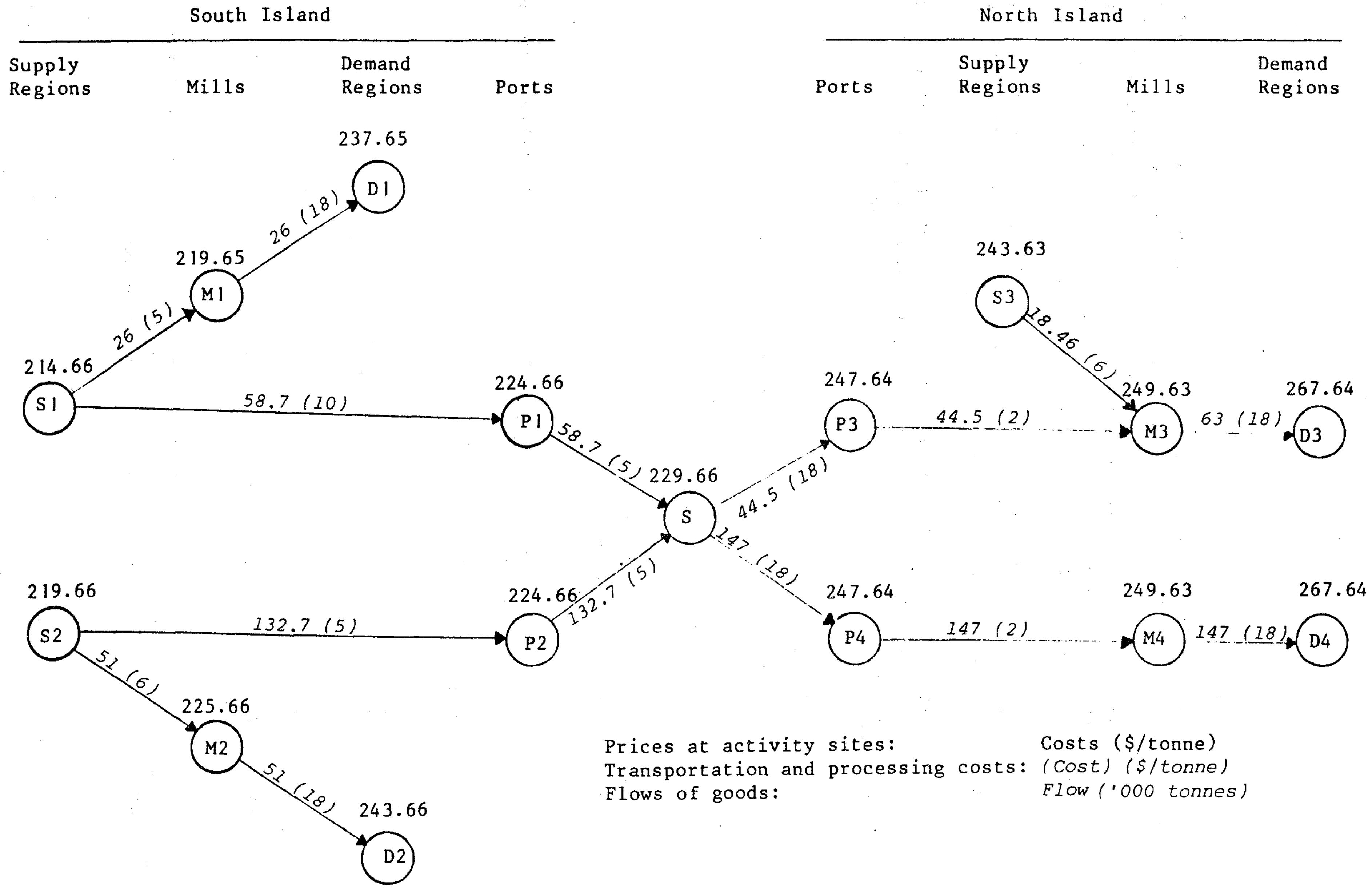
(3) North Island demand region 1 (D3)
$D3 = 63$

(4) North Island demand region 2 (D4)
$D4 = 147$

Results for Model I are presented diagrammatically in Figure 3. Flows of goods between activity sites and the prices at these sites are included. Note that all transport costs are constants.

FIGURE 3

Diagrammatic Results Model I



4.2 Model II

Economic equilibrium implies all product supplies and demands are equal at all trading sites. Economic equilibrium is achieved through the pricing mechanism. In order to realistically model any spatial equilibrium system, suppliers' responses to changes in price offered must be accounted for. This version of the example problem introduces basic supply functions for each of the supply regions. Since the problem is only concerned with a single commodity the regional supplies were estimated as functions of the regional price offered. A functional relationship commonly used for this type of curve estimation is the power function of the following form:-

$$Y = aP^{b}$$

where

P is the price offered for commodity
Y is the supply
a is a constant
b is the price elasticity of supply

This type of function allows either constant, increasing or decreasing marginal productivity and allows direct usage of supply elasticity estimates. The elasticities used for the supply functions were estimated by Rich and Zwart [11] with the resulting supply relationships as follows:

(1) $S1 = 3.38 \; P_1^{.6}$
(2) $S2 = 1.43 \; P_2^{.9}$
(3) $S3 = .23 \; P_3^{.8}$

P_i is the price offered per tonne in region i.

The resultant solution varied minimally from that for Model I, but could have implications if the model were shocked in some way i.e. a policy change (e.g. cheap regional development loans leading to lower production costs; a change in regional price to encourage/discourage regional production).

4.3 Model III

In this version of the model the concept of economies of scale experienced in New Zealand milling were introduced. Although many factors such as location, age of plant, specialisation and product differentation, depreciation and other accounting procedures distort the observed scale effects in milling, it is possible to fit a representative function showing the general relationship between cost of milling and mill size. Care must be taken that any a priori expectations, which may have been established about the production process, are consistent with the functional form of the relationship estimated. French [12] notes that milling operations which involve large capital inputs relative to labour inputs are likely to show greater economies of scale; this is the case with flour milling. Leath and Blakely [13] report that some flour mills in the United States have an annual output of 600,000 tonnes of flour. This is three times the New Zealand annual demand. This might suggest no upper limit or internal diseconomy of scale applicable to New Zealand milling operations, although the combined cost of milling and other activities certainly may create net diseconomies.

A functional relationship commonly used to represent decreasing cost functions which do not have an upper limit, is:

$$Y = \alpha X^{\beta}$$

where Y = processing cost per unit
α = positive constant
β = negative power
X = quantity of product processed

Data supplied by the New Zealand Flour Millers' Association (1979), were used (Borrell and Zwart [1]) to estimate the milling cost function as:

$$MC_i = 145\, M_i^{-.18578}$$

where MC_i = milling cost ($/tonne)
M_i = throughput in tonnes

To ensure the algorithm did not cycle between solutions without converging on a unique solution, an iterative routine similar to the approach adopted by Stammer [14] was linked to the algorithm. Only two iterations were required to reach convergence, although this is more a reflection of the stability of the example problem. The results are shown diagrammatically in Figure 4. The solution for this version does not vary significantly from that for the previous version in either regional production or price levels. However changes may have occurred if a different milling cost function was estimated for individual mills. The introduction of this type of cost function also provides a realistic way to evaluate the value of introducing new technology or new milling facilities through the resulting changes in the milling cost functions.

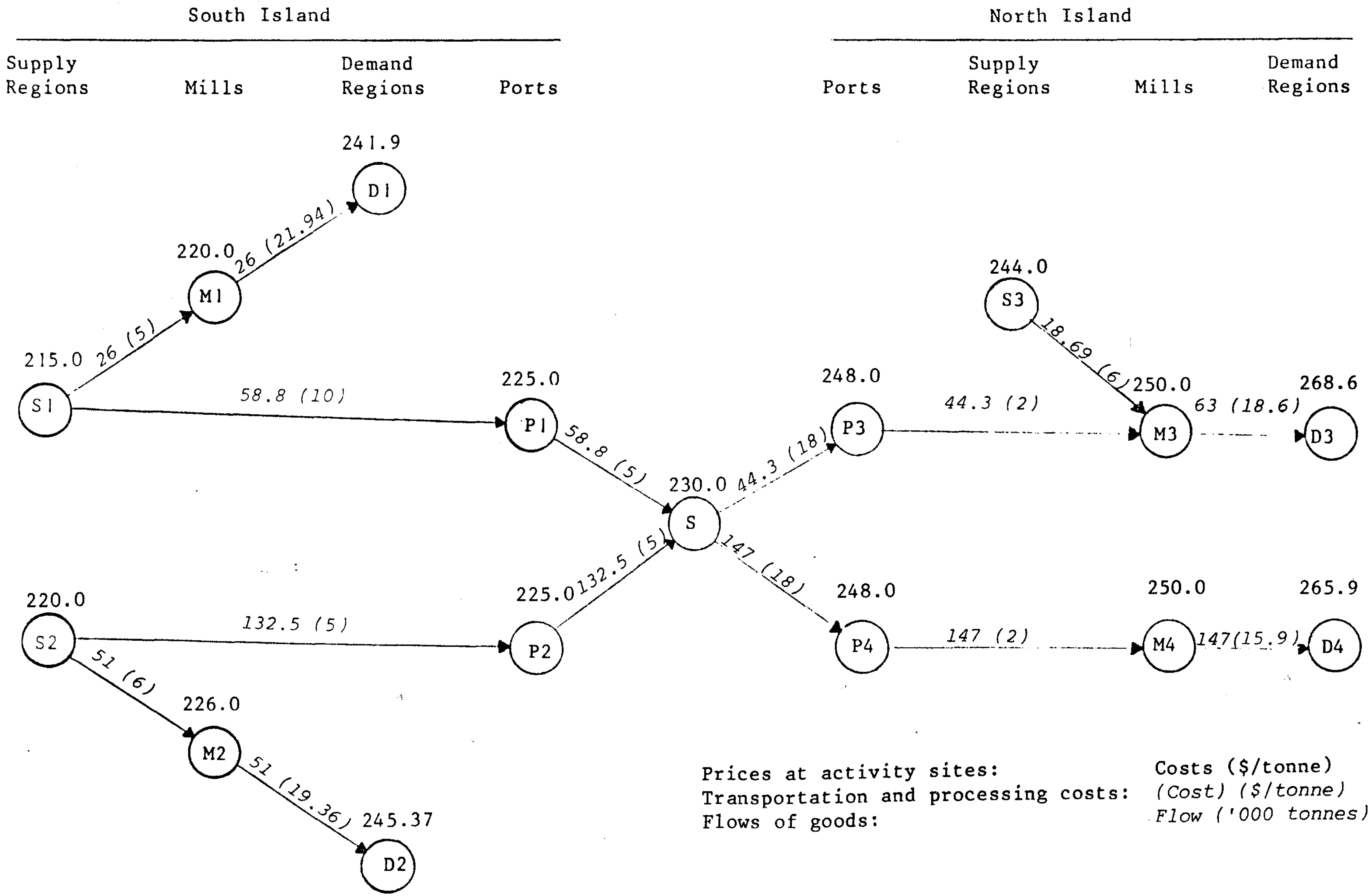
4.4 Model IV

The cost of most transportation activities consists of an initial capital investment (fixed cost) in plant and a per unit cost (running cost) for each unit of throughput.

As throughput rises the total cost (fixed cost + variable) per unit decreases at a decreasing rate. This type of decreasing cost function was introduced to model port storage and handling costs at the port of dispatch (South Island ports). The function used was that estimated by Borrell and Zwart [1] and was as follows:

FIGURE 4

Diagrammatic Results Model III



$$PC_i = 4 + \frac{140}{P_i}$$

where PC_i = port costs per tonne of wheat handled,
4 = constnt wharfage, segregation and cleaning costs,
140 = fixed cost of amortised inflation adjusted capital, interest and fixed annual operating cost, including rent, and
P_i = throughput of wheat

The algorithm was again used in conjunction with the iterative routine with convergence to a stable solution within two iterations. The solution is illustrated in Figure 5.

Note that in this solution flows have not changed much but prices have, meaning more accurate pricing.

4.5 Model V

Some forms of transportation are characterised by large fixed costs and minor variable costs. This is certainly the case when considering the economies of bulk shipping. This version of the model incorporates the destination port handling and storage costs and the shipping costs. The form of the cost function is of a similar nature to that used in Model IV and is as derived by Borrell and Zwart [1]. Shipping and off-loading port charges were related to throughput by:

$$PC_j + s = 1 + \frac{200}{P_j} + \frac{3000}{S}$$

where PC_j = off-loading at port j (per tonne), j = 3,4
S = Total quantity shipped ('000s tonnes)
P_j = Quantity off-loaded at port j in tonnes

The costs from North Island ports to North Island mills were not affected by these changes. Diagrammatic results are presented in Figure 6. As with version IV, flows have not altered significantly but prices have lead to more accurate pricing.

FIGURE 5

Diagrammatic Results Model IV

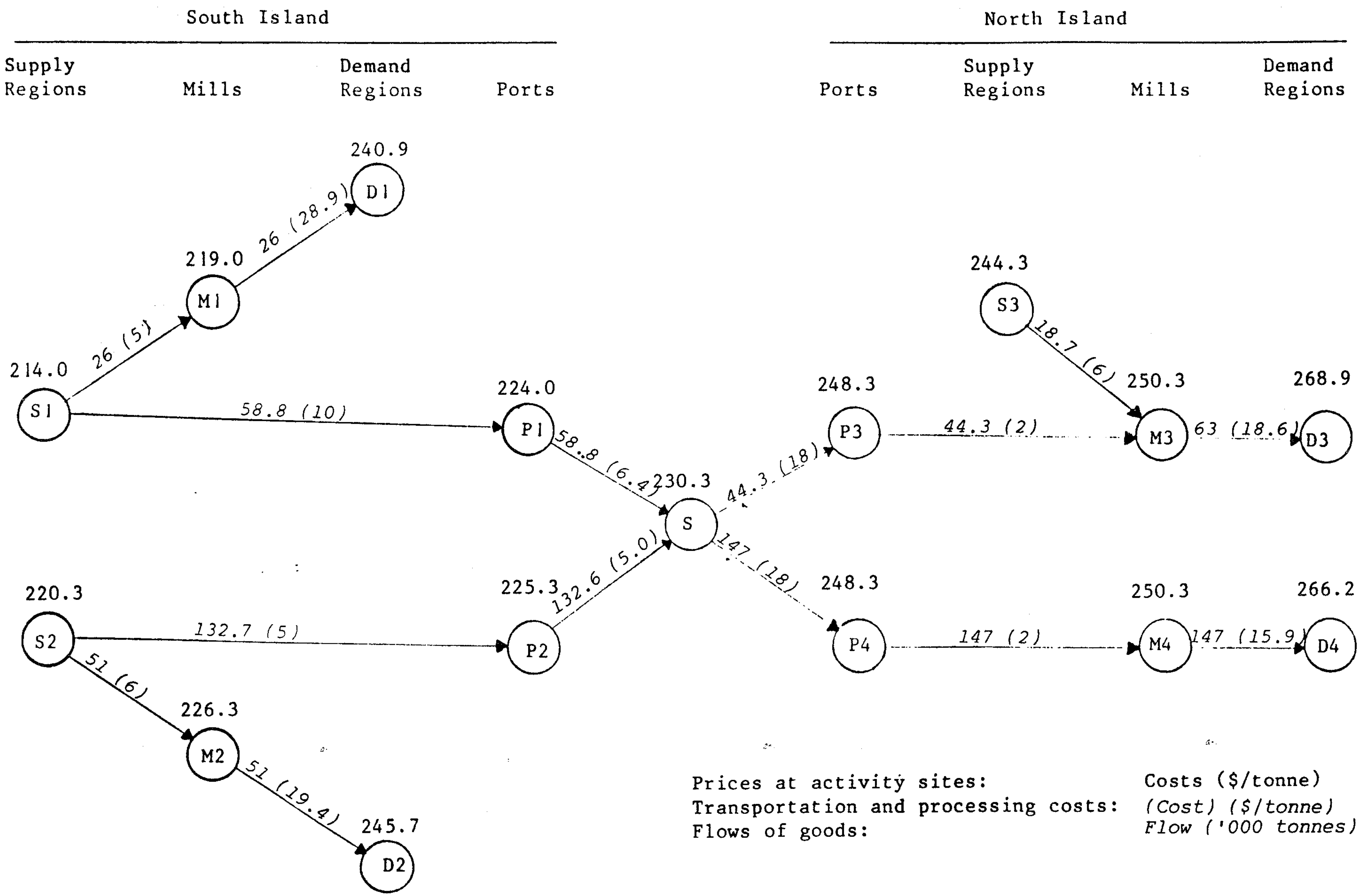
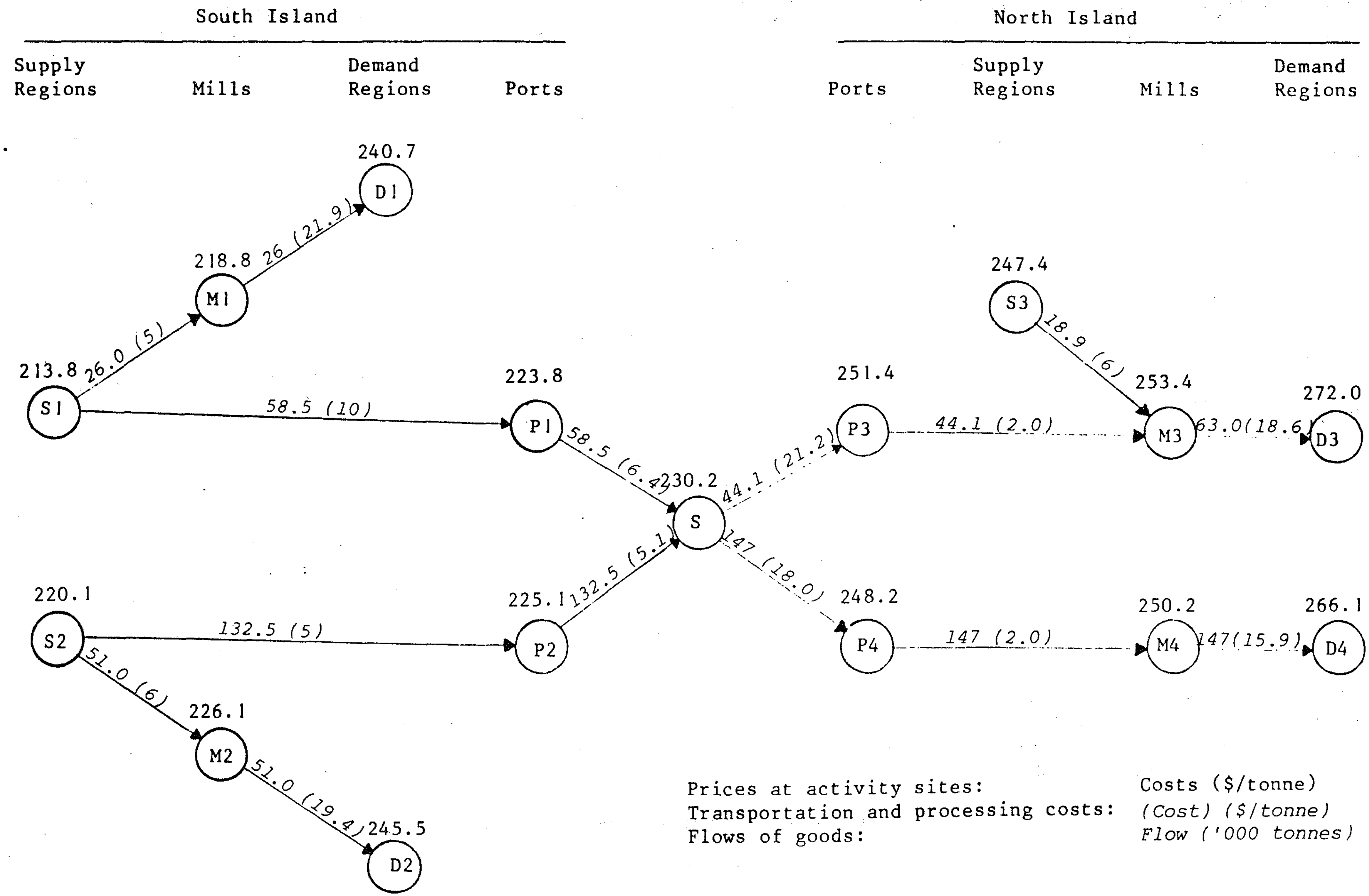


FIGURE 6

Diagrammatic Results Model V



SECTION 5

CONCLUSIONS

The Sandwich Algorithm is capable of handling much of the inherent non-linearities associated with spatial equilibrium analysis. This is particularly true when considering supply and demand curves and the economies and diseconomies of scale involved in both processing and transportation activities.

The example used here to demonstrate the use of the algorithm was a reduced version of a problem previously solved using linear programming techniques. This provided a convenient method of checking and comparing the results obtained through the two solution methods. The general characteristics of the solutions (flows between market sites, quantities processed) achieved by the methods did not vary greatly, although the differences would have become more apparent if the model had been used to simulate policy changes. The accuracy of the algorithm appears very good and seems to be limited only by the tolerance levels set either manually or inherent in the computer being used.

Solution times achieved by the algorithm were reasonably fast (21 seconds VAX 11/780 Model I). In addition to a reasonably fast solution time the algorithm required only small amounts of memory. For these reasons the algorithm seems well suited for use on micro computers.

Prices at each activity site are part of the output from the algorithm. For the wheat problem, used as the example, the algorithm provides an ideal way of evaluating the costs to both consumers and producers of having equalised regional pricing. In addition the system distortions imposed by milling quotas can also be readily examined via the algorithm.

This paper has demonstrated that increasingly realistic models can be developed to handle non-linearities in production response and transportation costs. In addition, techniques now available to solve these problems are accurate, easily used, computationally fast, and do not require large amounts of computer memory.

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