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CONSEQUENCES OF SMALL RICE FARM MECHANIZATION PROJECT

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A 0-1 INTEGER PROGRAMMING ALGORITHM FOR OPTIMAL SELECTION OF MUTUALLY EXCLUSIVE MACHINERY SETS

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Oram et al (1979) have estimated the current value of expected tractor and draft equipment investments by Asian countries between 1975 and 1990 at $3.95 billion. Considerable additional investment will doubtless be made in irrigation pumps, crop-care machinery, threshers, and post-harvest equipment. Although much of this equipment can and probably will be supplied by established manufacturers in developed countries, there is growing concern about the appropriateness and foreign exchange costs of such imported machinery.

An alternative is to encourage development of an indigenous farm machinery industry based on the local artisans' workshops so prevalent in much of South and South East Asia. Given sufficient encouragement, in terms of availability of appropriate basic designs, guidance on manufacturing, and assistance with marketing, some of these small businesses should expand rapidly and provide the foundations for a viable local industry. The Farm Machinery Development Program of the International Rice Research Institute (IRRI) provides one mechanism through which this objective can be achieved.

The identification, design and dissemination of appropriate agricultural machines is a complex multidisciplinary problem requiring integration of the skills of engineers, economists and agricultural scientists. The prime roles of the economist are to provide ex ante information on the likely acceptability and impact of machinery and to

assist in establishing research priorities. To be effective economists must be involved at the conceptualization stage, and continue through design testing and final machinery release. Failure to evaluate proposals adequately will result, at best, in a waste of resources and may, at worst, severely restrict the development of a potentially major industry.

The simplest and most widely used technique by which engineers evaluate machinery is private (to the farmer) benefit-cost analysis. Fixed and variable cost estimates typically depend on standardized formulas (Kepner, Bainer and Barger 1972, Hunt 1973). Machine ownership benefits - such as timeliness, yield increases and cropping intensity increases - are more difficult to quantify. Maranan (1981) assumed an implied rental rate for preparation of own land, and hence income for the tractor activity, equal to the average custom rate. Yet a farmer would be expected to prepare his own land at the optimum time and allocate any remaining time to custom operations. This implies a higher shadow price for own-farm operations than the average custom rate. An alternative (Juarez and Duff 1977) is to compare costs on the basis of equivalent work by an alternative power source. For example a two-wheel tractor could be evaluated by comparison with the cost of doing an equivalent amount of work using a water buffalo. The benefit would then be the costs saved by not using the water buffalo. This technique assumes that one is able to define adequately an equivalent amount of work.

Such simple benefit-cost approaches ignore possible interactions of machinery ownership and use with the rest of the farmer's resource base and cropping pattern. Machinery acquisition usually causes large changes in factor proportions which would be expected to result in altered cropping patterns. Whole-farm planning techniques, such as mathematical programming and simulation analysis, provide a mechanism for incorporating these changes.

Donaldson (1975) developed simulation models to assess cereal seeding and harvesting considering machine performance, crop yields, and losses due to untimely operations under different weather conditions. Power requirements, machinery selection, operations scheduling and costing for a given farm plan have also been considered (Hughes and Holtman 1976) as have timeliness losses (Edwards and Boehlje 1980). Monte Carlo simulation (Donaldson and Webster 1968) offers an extremely flexible approach to simultaneous selection of machinery sets and cropping pattern, but no applications appear to have been undertaken.

Although only limited inferences can be drawn, there have been several applications of linear programming to farm planning with a fixed machinery set (e.g. McCarl et al 1977). Integer programming has been applied to machinery selection in developed countries (Colyer and Vogt 1967) as well as developing countries (Gotsch and Yusuf 1975, Danok, McCarl and White 1978). Gotsch and Yusuf formulated a model to study the implications to Pakistan of withdrawing tractor import subsidies. Whilst recognising the potential of custom and cooperative operations, they considered them insufficiently developed to include in the model. Danok, McCarl and White used an integer programming model for simultaneous machinery selection and crop planning of a state farm in Iraq. Constraints were required to ensure certain machines were only selected in combination with others and combinations were prohibited.

An alternative approach, in which machinery is grouped into sets rather than sets being selected from individual machines, was developed by Danok, McCarl and White (1980). Solutions can be obtained either by integer programming, or by solving for all feasible machinery sets using linear programming. Linear programming would be a tedious

process if there were more than a few options to evaluate, but the large number of solutions would provide the basis for a more thorough analysis.

Other than for the final simplified case all of the mathematical programming procedures discussed above required the availability of an integer programming algorithm. In many developing countries neither the algorithms nor the expertize to implement them are readily available. In the remainder of this paper we developed an alternative procedure for obtaining an integer programming optimum through solution of a limited number of linear programming problems, the algorithm for which is more widely available. The procedure is subsequently applied to farm machinery investment problem for a typical irrigated farm in Nueva Ecija.

Theoretical model and solution procedure

The integer programming problem (IP) can be stated as:

(1) $$\max z = c_1x_1 + c_2x_2$$

subject to

(2) $$A_1x_1 + A_2x_2 \leq b$$

$$\lambda x_1 = 1$$

$$x_1 = 0, 1$$

and $$x_2 \geq 0$$

where z is the objective function value

c_1 is $1 \times l$ vector of return or cost coefficients associated with 0-1 integer variables,

x_1 is a $l \times 1$ vector of mutually exclusive 0-1 variables,

c_2 is a $1 \times n$ vector of return or cost coefficients associated with continuous variables,

x_2 is a $n \times 1$ vector of continuous variables,

A_1 is a $m \times l$ matrix of coefficients in constraints associated with 0-1 variables,

A_2 is a $m \times n$ matrix of coefficients in constraints associated with continuous variables,

b is a $m \times 1$ vector of resources or right hand sides, and

λ is a summation vector - a $1 \times l$ vector containing 1 as each element

The mutual exclusivity and 0-1 conditions, imposed on x_1 by the 0-1 restriction and the constraint $\lambda x_1 = 1$, ensure that only one element of x_1 can be equal to one and all others must be zero. By arbitrarily selecting the kth element, x_1^k, to be one and setting all other elements to zero the problem can be rewritten in linear programming (LP) form as:

$$\max z(x_1^k) = c_1^k x_1^k + c_2 x_2 \tag{3}$$

subject to

(4) $$A_2 x_2 \leq b - A_1^k x_1^k$$

and

$$x_2 \geq 0$$

where c_1^k is the kth element of the vector c_1, and

A_1^k is the kth column of the matrix A_1.

An obvious way to solve the IP (equations 1 and 2) is to solve the LP (equations 3 and 4) sequentially for all x_1^k and then select the optimal solution. While practical for relatively limited problems it becomes tedious as soon as a realistic number of integer variables are considered. Solution efficiency can be greatly improved by eliminating the requirement that all of the LP problems must be solved to locate the optimum IP solution. This is achieved as follows.

The dual of the LP problem is

(5) $$\min z(x_1^k) = c_1^k x_1^k + u(b - A_1 x_1^k)$$

subject to

(6) $$u A_2 \geq c_2$$

and

$$u \geq 0$$

where u is a 1 x vector of dual variables associated with the vector of resource availabilities, b.

Garfinkel and Nemhauser (1972) have shown that, if the dual has an optimal solution for any x_1^k, a constraint on x_1 can be specified as

$$(7) \qquad (-c_1 + u^k A_1)\, x_1 \leq -\underline{Z} + u^k b$$

where $\underline{Z}$ is the best known value of the objective function for the LP problem and u^k is the row vector of optimum values from solution of the dual problem. For those cases where the dual is unbounded, that is there is no feasible solution to the primal LP problem, x_1^k is inadmissible. An optimal solution to the dual problem also provides a value for $\underline{Z}$.

Since the problem has been formulated with a set of mutually exclusive integer vectors and infeasible options can be eliminated during model specification, the existence of either an infeasible or unbounded solution to the primal problem will indicate the existence of a specification error in the primal model. This may not be the case for more general models (Garfinkel and Nemhauser 1972). Solution of the primal problem will provide a lower bound on the objective function, $\underline{Z}$ and a vector of resource shadow prices, u^k, which may be combined with b, c_1 and A_1 to evaluate inequality 7.

Partitioning A_1 into l vectors, a_l, each of dimension m x 1, inequality 7 can be rewritten as

$$(8) \qquad \sum_{j=1}^{l} (-x_{1j} + u^k a_{1j})\, x_{1j} \leq -\underline{Z} + u^k b,$$

Since all x_{1j} are 0-1 and mutually exclusive, inequality 8 can be solved for each x_1 by sequentially setting one variable to one and all others to zero. Those x_{1j} for which the constraint is not violated are retained for future consideration.

All that remains is to determine the sequence for selecting variables for consideration. From inequality 8 it is clear that the smaller, or more negative, the value of $(-c_{1j} + u^k a_{1j})$ the less likely a x_{1j} is to be eliminated. Hence the x_{1j} with the smallest value is selected for the next cycle. It should however be noted that since the vector of shadow prices, u^k, is specific to the optimum solution of the LP with x^k as the integer variable, selection of an alternative variable will likely change the shadow prices and may alter the ranking of the x_{1js}. This will limit the number of options eliminated at the end of that cycle and provide a new x_{1j} for consideration.

The procedure systematically generates new constraints on x_1 whenever a new vector of dual values, u, is generated from solution of the LP, and revises the constraints with new $\underline{Z}$ whenever an improved $\underline{Z}$ is available. Both changes can result in elimination of some of the machinery sets. The process is finite and continues until either the set of reduced constraints indicates the optimal solution or all sets have been enumerated.

A flowchart for the procedure is in Figure 1 and a brief description now follows.

Inequality 7 can be written as

(9) $$\sum_{j=1}^{l} \alpha_{ij} x_{lj} \leq \beta_l$$

where $\alpha = (-c_l + u^k A_l)$ and

$\beta = -\underline{Z} + u^k b$

Step 1. Let T be the set of inequality 9 specified so far.

Initially T is empty.

Let Q be the set of x_ls not currently zero in the optimal solution.

Initially Q contains all x_l

Let $\underline{Z}$ be the best known lower bound on the objective function. Initially $Z = -\infty$

Step 2. If Q contains at least one element go to step (3). Otherwise examine $\underline{Z}$

If $Z = -\infty$, there is no feasible solution. Terminate.
If $Z \neq -\infty$, the solution most recently recorded in step (5) is optimal. Examine previously recorded solutions in step (5) for multiple optima and terminate.

Step 3. If T is empty select x^k arbitrarily and go to step (4). Otherwise examine the inequality most recently placed in T at step (7). Select the x_j from Q which has minimum α_j, and designate as x_l^k.

Step 4. Eliminate x^k from the set Q and solve the LP with $x_1^k = 1$. If the solution is optimal go to step (5). Otherwise go to step (2).

Step 5. If the optimal value of objective function, z^* is less than $\underline{Z}$ go to step (7). If $Z^* \geq \underline{Z}$, record the solution. If $\underline{Z}^* > \underline{Z}$, set $\underline{Z} = Z^*$ for all inequality in T.

Step 6. If T is empty go to step (7). Otherwise revise all the inequalities in T with $\underline{Z}$ and go to step (7).

Step 7. Solve inequality (9) with new u^k and $\underline{Z}$, place in T and go to step (8).

Step 8. Delete all x_{1j} from Q which have $\alpha_{ij} > \beta_i$ in any inequality of T and go to step (2).

AN ILLUSTRATIVE APPLICATION

The procedure was applied to a machinery selection problem for a typical irrigated rice farm in Nueva Ecija, Philippines. Data over 300 farms, collected as a part of the Consequences of Small Rice Farm Mechanization Project (USAID contract ta-c-1466), together with machine specific coefficients obtained from IRRI's Agricultural Engineering Department, provided the basis for model specification.

Detailed matrix presentation is in the Appendix. The objective function consists of the net income from crop sales, machine rental, and other resource rental less the annual fixed costs of machine ownership, costs of renting in machines and costs of renting in other services. The model is defined by six constraint sets (A2 to A7 in the Appendix), upper bounds on the renting in and renting out of machinery and other resources (A8) and the usual non-negativity

restrictions (A9). All field operations for crop production must be performed at the appropriate time using either the purchased machinery set or rented in machinery (A2). Total machinery use for any operation in all crops together with renting-out must not exceed the capacity of machinery available from ownership and renting in for undertaking that operation (A3). An overall constraint is imposed on all operations the power requirement for which must not exceed owned plus rented machine capacity (A4). Cash, land, water, and technical requirements of crop production must be satisfied at the correct time and transferable resources can be made available at a later time (A5). Only one machinery set can be adopted (A6), and this must be purchase as an entire unit (A7).

The model includes conventional activities as well as machinery purchase. Crop production activities are defined by crop type, variety and planting time. Machinery renting activities are included to permit either renting in or renting out of machinery. Similarly resource adjustment activities are included to permit renting in and renting out of other resources, and input supply activities to permit purchase of fertilizer, insecticide, fuel, and other inputs. Resource transfer activities are specified so that surplus resources and intermediate products from one period can be made available in subsequent periods.

Machinery purchase activities are not included explicitly in the model. Machinery is selected from the available range on the basis of a predetermined mutually exclusive set which is defined exogenously. A machinery set may consist of any, all, or none of a power source (two-wheel tractor, carabao), engine, implements (plows, harrows) and other machines (threshers, transplanters). Units included in a set must be technically compatible, and the set should be usable for the intended purposes without additional machine components. Hence it is possible to have a single machine comprising

a set, in addition to that machine being in several other sets, so long as each set comprises a unique combination.

In addition to the farmer's existing power tiller, the model was specified for machinery sets to be derived from a carabao, two sizes of power tiller (PT3 and PT8), two sizes of reaper (R1 and R1.6), two sizes of thresher (TH7 and TH8), four sizes of gasoline engine (GE3, GE8, GE10 and GE16), two sizes of diesel engine (DE6 and DE8) and a transplanter. Machinery sets were formulated from these options in accordance with technical requirements, and subject to the exclusion of "unreasonable" combinations. For example power tillers could only be linked to engines of the appropriate size, and only one of the small (TH7) and large (TH8) axial flow thresher was permitted.

Figure 2 shows part of the resultant tree of feasible machinery sets. Given a ₱25,000 upper limit on investment costs, 76 potential machinery sets were identified. Solution of the LPs associated with all of machinery sets would have been a tedious process. However, the proposed procedure required solution of only eight LP problems.

Results

Iterations of the solution procedure are set out in successive columns of Table 1. Solution was initiated by solving the LP with a machinery set comprising the existing power tiller. This gave an optimal value of ₱14,857. On the basis of the lower bound, machinery set 42 (transplanter) was eliminated and machinery set 34 (TH7, GE8, PT8 and R1.6) selected for the second iteration. Solution of the revised LP produced a higher objective function value, ₱25,718, and hence a revised value for $(-\underline{Z} + u^k b)$. This

resulted in elimination of 25 machinery sets and selection of set number 33 for the third iteration. Again, the LP solution produced a higher objective function value requiring revision of $(-\underline{Z}+u^k b)$, and identifying machinery set 25 for the fourth iteration. Solution of iterations four through eight produced no improvement in the objective function value but resulted in elimination of all other machinery sets through revised values of the other vectors. The optimum solution was defined as the LP solution of the problem with a machinery set consisting of the existing power tiller, TH8 and GE16 (set number 33). This solution, which was identified at the third iteration, yielded a gross margin of ₱29,380.

The optimal machinery set may serve as a good starting point for solving further problems which differ only in a few parameters from the initial problem, such as in the case of parametric analysis. Although it may provide a value of $-\underline{Z} + u^k b$ which will eliminate many of the sub-optimal machinery sets several further iterations will probably be required to locate the optimum solution.

CONCLUSIONS

Evaluation of alternative mechanization options is one of the most important roles of an economist working collaboratively with agricultural engineers. The provision of timely and comprehensive analyses of the feasibility and ranking of alternative research strategies can provide guidance in research resource allocation. One of the major areas for this research is the evaluation of machines from the farmer's perspective.

Although considerable work has been undertaken in evaluating machinery investment within a whole-farm framework, the IP algorithms

and computer hardware required are rarely available in developing countries. This prompted us to reformulate the machinery selection problem as a 0-1 IP model with mutually exclusive integer variables. A solution procedure was developed which used the more readily available LP algorithm and allowed elimination of many of the potential machinery sets without solving the related LPs.

Application of the procedure to a machinery selection problem for a typical small, irrigated rice farm in Nueva Ecija, Philippines demonstrated its efficiency. As currently formulated problems are evaluated by first solving the LP problem using a conventional package, then manually eliminating suboptimal machinery sets and selecting the one for the next trial. However, it would be relatively easy to combine these stages in an iterative computer algorithm which would facilitate problem solution by using the optimal solution for one iteration as the starting point for the next.

Table .. Generation of Constraints for Elimination of Sub-optimal Machinery Sets.

		COEFFICIENTS OF LEFT HAND SIDES OF INEQUALITY (9): $-e + u^k A_i$							
		k = 1	34	33	25	41	22	31	39
1.	Existing PT	-	-	-	-	-	-	-	-
2.	Carabao	- 831	- 847	-a/	-	-	-	-	-
3.	PT3 + CE3	- 2472	- 251	-	-	-	-	-	-
4.	PT3 + DE5	- 6602	+ 130	-	-	-	-	-	-
5.	PT8 + CE8	- 4606	- 1459	-	-	-	-	-	-
6.	PT8 + CE10	- 3798	- 1251	-	-	-	-	-	-
7.	PT8 + DE6	- 5922	- 2049	-	-	-	-	-	-
8.	PT8 + DE8	- 5727	- 1638	-	-	-	-	-	-
9.	TH7 + CE8	-12481	- 6479	-	-	-	-	-	-
10.	TH7 + CE10	-14031	- 7150	-	-	-	-	-	-
11.	TH7 + DE6	-11030	- 8589	+ 1210	-	-	-	-	-
12.	TH7 + DE8	-12436	- 8361	+ 1755	-	-	-	-	-
13.	TH8 + CE8	-21304	-17171	+ 3770	-20602	+ 1358	-20660	+ 3770	+3770
14.	TH8 + CE10	-22875	-17838	+ 4129	-22072	+ 4129	-	-	-
15.	TH8 + CE16	-30512	-24791	+ 4292	-29092	+ 4292	-	-	-
16.	PT3 + CE3 + R1	-45852	+ 490	-	-	-	-	-	-
17.	PT3 + DE6 + R1	-51458	+ 1253	-	-	-	-	-	-
18.	TH7 + DE6 + PT3	-18734	- 9025	- 3499	-	-	-	-	-
19.	TH7 + CE8 + PT8	-17546	- 8399	- 1753	-	-	-	-	-
20.	TH7 + CE10 + PT8	-18184	- 9069	- 1358	-	-	-	-	-
21.	TH7 + DE6 + PT8	-18051	-11740	- 2819	- 9836	- 6070	- 9418	-	-
22.	TH7 + DE8 + PT8	-19456	-11299	- 2256	-11238	- 6086a	-	-	-
23.	PT8 + CE8 + R1.6	-59592	- 9020	-70702	-	-	-	-	-
24.	PT8 + CE10 + R1.6	-58785	- 9814	-70449	-	-	-	-	-
25.	PT8 + DE6 + R1.6	-60965	-12574	-72014a	-	-	-	-	-
26.	PT8 + DE8 + R1.6	-60710	-12182	-71507	+ 3611	-	-	-	-
27.	Exist. PT + TH7 + CE3	-18046	- 8921	+ 2240	-	-	-	-	-
28.	Exist. PT + TH7 + CE10	-19617	- 9591	+ 2559	-	-	-	-	-
29.	Exist. PT + TH7 + DE6	-16596	-12261	+ 1210	-10969	- 4597	-10033	-	-
30.	Exist. PT + TH7 + DE8	-18001	-11820	+ 1759	-12353	- 4613	- 8681	-	-
31.	Exist. PT + ~~TH7 + CE8~~	-26670	-19612	+ 3710	-20602	- 1774	-22078a	-	-
32.	Exist. PT + TH7 + CE10	-28440	-20279	+ 4129	-22043	+ 1415	-22007	+ 4129	-
33.	Exist. PT + TH8 + CE16	-29177	-27233a	-	-	-	-	-	-
34.	TH7 + CE8 + PT8 + R1.6	-72533b/	-	-	-	-	-	-	-
35.	Carabao + TH7 + CE8	-13411	- 7782	+ 1309	-	-	-	-	-
36.	Carabao + TH7 + CE10	-14982	- 8452	+ 1668	-	-	-	-	-
37.	Carabao + TH7 + DE6	-11963	- 9892	+ 279	-	-	-	-	-
38.	Carabao + TH8 + DE8	-13367	- 9663	+ 828	-	-	-	-	-
39.	Carabao + TH8 + CE8	-22235	-18474	+ 2839	-20083	+ 2831	-21919	+ 2831a	-
40.	Carabao + TH8 + CE10	-23805	-19149	+ 3198	-21524	+ 3190	-21848	+ 3190	+ 4648
41.	Carabao + TH8 + CE16	-31742	-26095	+ 3361	-29174a	-	-	-	-
42.	Transplanter	+ 581	-	-	-	-	-	-	-
43.	Transplanter + Set 1	- 4985	- 1860	-	-	-	-	-	-
44.	Transplanter + Set 2	- 350	- 266	-	-	-	-	-	-
45.	Transplanter + Set 3	- 1891	+ 330	-	-	-	-	-	-
46.	Transplanter + Set 4	- 6021	+ 711	-	-	-	-	-	-
47.	Transplanter + Set 5	- 4025	- 878	-	-	-	-	-	-
48.	Transplanter + Set 6	- 3217	- 643	-	-	-	-	-	-
49.	Transplanter + Set 7	- 5341	- 1468	-	-	-	-	-	-
50.	Transplanter + Set 8	- 5146	- 1057	-	-	-	-	-	-
51.	Transplanter + Set 9	-11900	- 5859	-	-	-	-	-	-
52.	Transplanter + Set 10	-13470	- 6569	-	-	-	-	-	-
53.	Transplanter + Set 11	-10449	- 8008	-	-	-	-	-	-
54.	Transplanter + Set 13	-11855	- 7280	+ 2336	-	-	-	-	-
55.	Transplanter + Set 13	-20723	-16590	+ 4351	-	-	-	-	-
56.	Transplanter + Set 14	-22294	-17257	+ 4710	-	-	-	-	-
57.	Transplanter + Set 15	-30231	-24211	+ 4873	-	-	-	-	-
58.	Transplanter + Set 16	-45271	+ 1071	-	-	-	-	-	-
59.	Transplanter + Set 17	-50877	+ 1834	-	-	-	-	-	-
60.	Transplanter + Set 18	-18153	- 8444	- 2918	-	-	-	-	-
61.	Transplanter + Set 19	-16965	- 7818	- 1172	-	-	-	-	-
62.	Transplanter + Set 20	-17601	- 8488	- 777	-	-	-	-	-
63.	Transplanter + Set 23	-59011	- 8439	-70121	-	-	-	-	-
64.	Transplanter + Set 24	-58204	- 9233	-69868	-	-	-	-	-
65.	Transplanter + Set 27	-17465	- 8339	+ 2821	-	-	-	-	-
66.	Transplanter + Set 28	-19036	- 9010	+ 3180	-	-	-	-	-
67.	Transplanter + Set 29	-16015	-11680	+ 1791	-10388	- 4016	- 9452	-	-
68.	Transplanter + Set 30	-17420	-11239	+ 2340	-11772	- 4032	- 8100	-	-
69.	Transplanter + Set 31	-26289	-19031	+ 4351	-	-	-	-	-
70.	Transplanter + Set 32	-27859	-19698	+ 4710	-	-	-	-	-
71.	Transplanter + Set 33	-28596	-26652	4873	-	-	-	-	-
72.	Transplanter + Set 36	-12830	- 7201	-	-	-	-	-	-
73.	Transplanter + Set 37	-14401	- 7871	2249	-	-	-	-	-
74.	Transplanter + Set 38	-11382	- 9311	860	-	-	-	-	-
75.	Transplanter + Set 39	-12786	- 9082	1409	-	-	-	-	-
76.	Transplanter + Set 40	-21654	-17893	3420	-19502	+ 3412	-	-	-
	$-\underline{r}$	= -14857	-25718	-29380	-29380	-29380	-29380	-29380	-29380
	$u^k b$	= +14857	+18480	+33672	+21480	+32584	+17236	+33372	+32284
Right hand sides c/	1: $-\underline{r}_1 + u^k b$	= 0	-	-	-	-	-	-	-
	2: $-\underline{r}_{34} + u^k b$	= -10861	- 7238	-	-	-	-	-	-
	3: $-\underline{r}_{33} + u^k b$	= -14523	- 10900	4292	- 7900	3204	-12144	+ 3992	3904

a/ - indicates the machinery set has been either enumerated or eliminated.

b/ - indicates machinery set selected for next iteration

c/ RHS of constraint under k = 1 revised twice using $-\underline{r}$ generated by k = 34 and k = 35. For k = 34 $-\underline{r}$ was revised once. No subsequent improvement on $-\underline{r}$ were generated.

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A1

APPENDIX

The farm matrix may be represented as:

Maximize

(A1) $$Z = - \sum_m C_m X_m + \sum_k \sum_t q_{k,t} Q_{k,t} - \sum_h \sum_f \sum_p s_{h,f,p} S_{h,f,p}$$

$$+ \sum_f \sum_m \sum_p t_{f,m,p} T_{f,m,p} - \sum_r \sum_p W_{r,p} W_{r,p} + \sum_r \sum_p y_{r,p} Y_{r,p}$$

Subject to

(A2) $$- \sum_m e_{f,m,p} L_{f,m,p} - \sum_h i_{f,h,p} S_{f,h,p}$$

$$+ \sum_k \sum_t a_{f,k,p,t} Q_{k,t} \leq 0$$

for all valid f, p

(A3) $$- \sum_m d_{f,m,p} X_m + \sum_m L_{f,m,p} + \sum_m T_{f,m,p} \leq 0$$

for all valid f, p

(A4) $$- \sum_f d_{f,m,p} X_m + \sum_f L_{f,m,p} + \sum T_{f,m,p} \leq 0$$

for all valid m, p

(A5) $$- B_{r,p} - W_{r,p} + Y_{r,p} + \sum_f \sum_m g_{r,f,m,p} L_{f,m,p}$$

$$+ \sum_k \sum_t h_{r,p,k,t,} Q_{k,t} + B_{r,p} + 1 \leq b_{r,p}$$

for all valid r, p

(A6) $$\sum_m X_m \leq 1$$

(A7) $$X_m = 0,1 \text{ for all } m$$

A2

(A8) all S, T, W and Y are bounded above and

(A9) all L, Q, S, T, W, Y, B $\geq$ 0

where:

Z	is the total net return,
C_m	is the fixed cost of machinery set m for the planning period,
X_m	is a 0-1 variable for ownership of machinery set in,
$q_{k,t}$	is net revenue per hectare from crop k planted at time t,
$Q_{k,t}$	is hectares of crop k planted at time t,
$s_{f,h,p}$	is cost per hour of operation f using hired machinery set h in period p,
$S_{f,h,p}$	is hours of hired machinery set h using operation f in period p,
$t_{f,m,p}$	is rental income per hour for operation f using machinery set m in period p,
$T_{f,m,p}$	is hours of renting out for operation f of machinery m in period p,
$w_{r,p}$	is cost per unit of renting in or purchasing resource/input r in period p,
$W_{r,p}$	is units of resource/input r rented in or purchased in period p,

A3

$y_{r,p}$ is revenue per unit from renting out or selling resource r in period p,

$Y_{r,p}$ is units of resource r rented out or sold in period p,

$e_{f,m,p}$ is capacity for field operation f in hectares per hour of purchased machinery set m in period p,

$L_{f,m,p}$ is hours of own farm operation f with machinery set m in period p,

$i_{f,h,p}$ is capacity for field operation f in hectares per hour of rented machinery set h in period p,

$a_{f,k,p,t}$ is the number of passes of operation f required in period p for crop k, planted at time t,

$d_{f,m,p}$ is the maximum number of hours of operations f provided by machinery set m in period p,

$B_{r,p}$ is the number of units of resource/input r transfered to period p from previous period,

$b_{r,p}$ is the number of units of resource/input r available in period p from farmer's endowment,

$g_{r,f,m,p}$ is the number of units of resource/input r required per hour of operation f with machinery set m in period p,

$h_{r,p,k,t}$ is the number of units of resource/input r required per hectare in period p for crop k planted at time t.

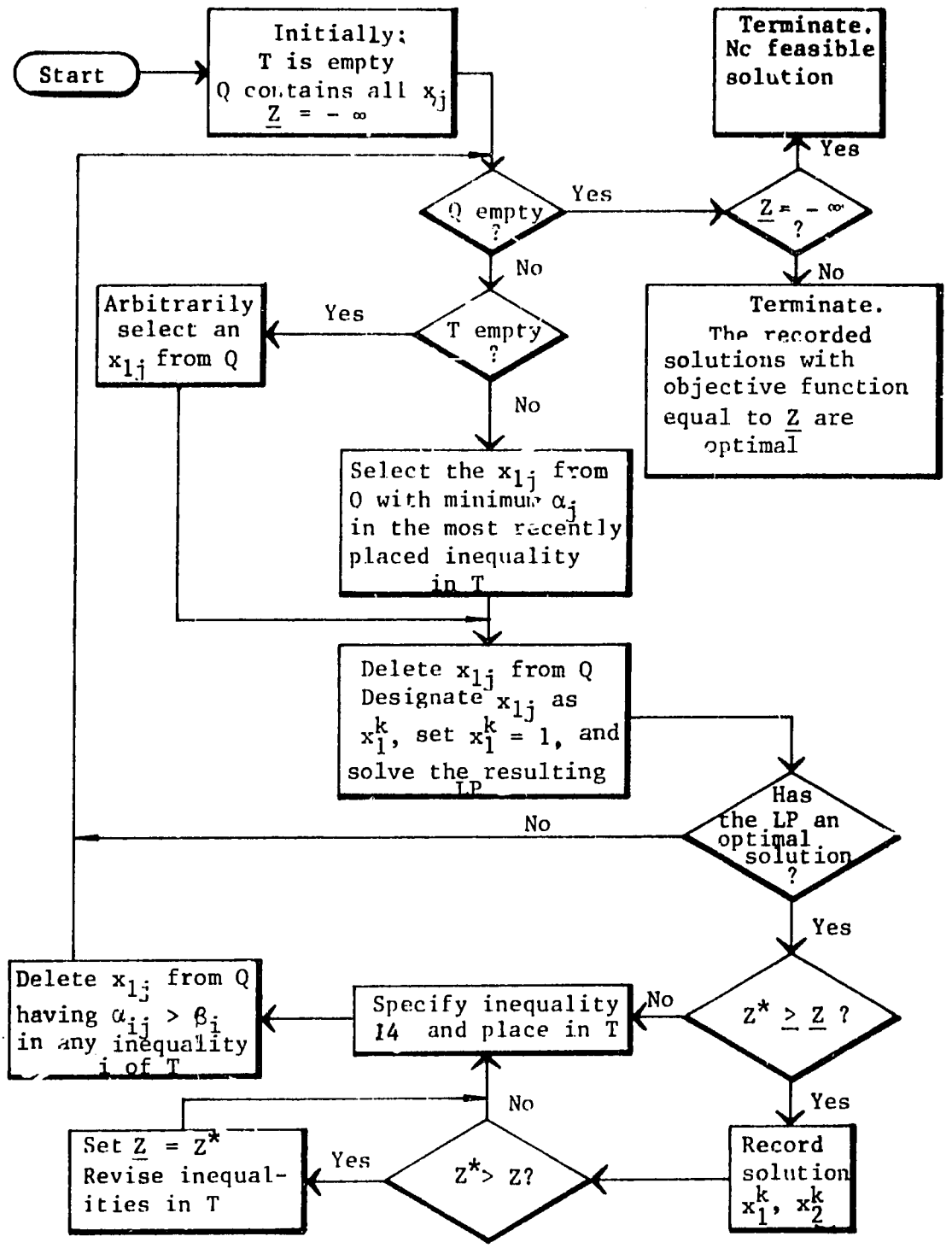

Figure 1. Flow Diagram of the Partial Enumeration Algorithm.

Notation: F. B. N. S. = Further branches not shown
F. B. N.P. = Further branching not possible
—||— = Constraint on capital prohibits the otherwise possible branch.
[ ] = Initial cost of machinery combination from origin to the node.

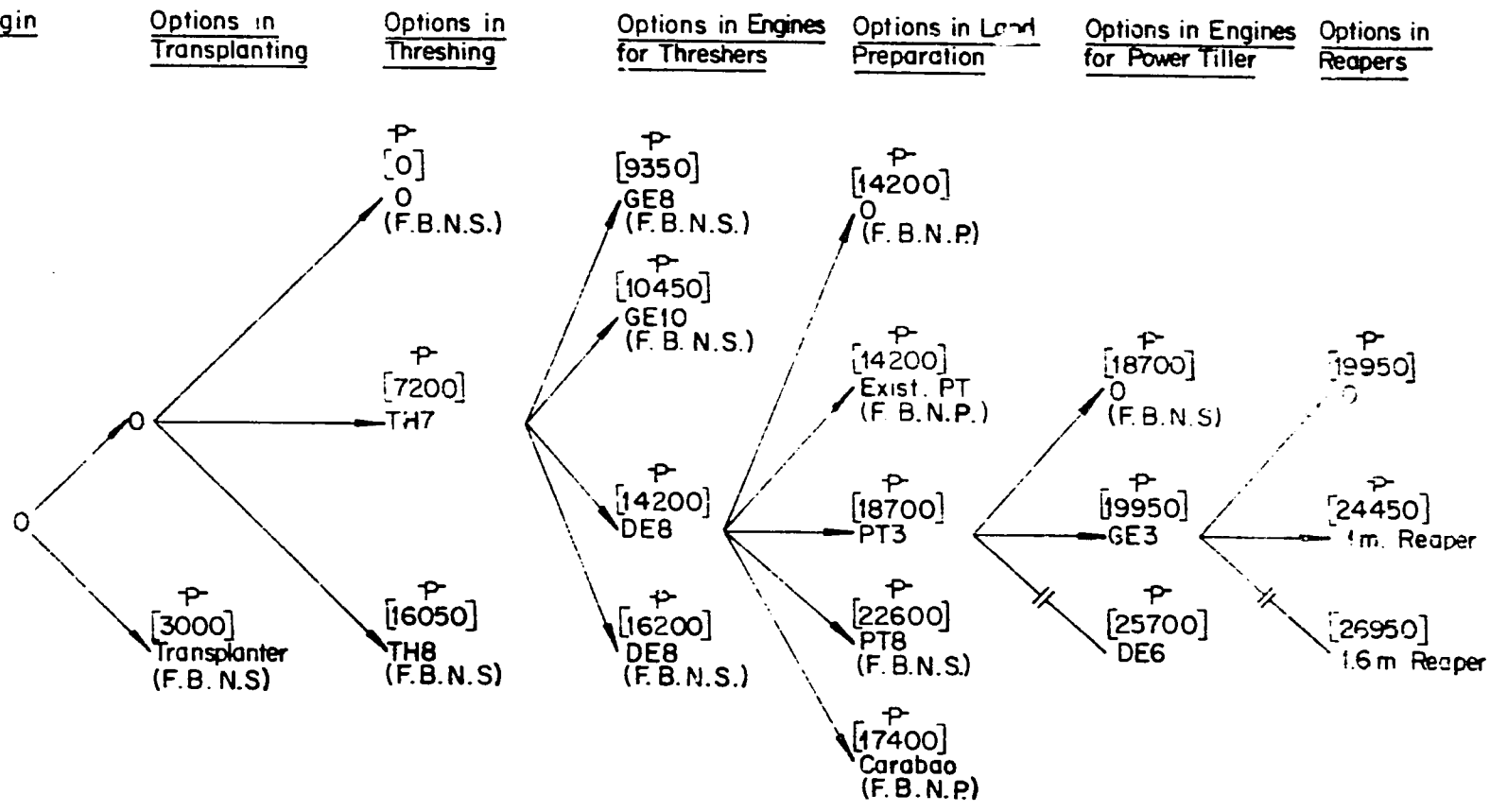

Figure 2. A Part of Tree of Feasible Machinery Sets.
Note: Machinery units along a unique path from origin at the left to a point where further branching is impossible constitute a unique machinery set.

CONSTRAINT	ACTIVITIES																RIGHT HAND SIE	
	Machinery Set Ownership	Borrow Long Term Capital	Borrow Cash for Season	Land Preparation (by Machinery Set)	Service Renting Out (by Machinery Set and Operation)	Service Renting In (by Machinery Set and Operation)	Crop Establishment (by Method)	Manual Labour Hiring (by Operation)	Operator Labour Hiring (by Operation)	Input Purchasing (by Period)	Crop Reaping (by Machinery Set)	Threshing (by Machinery Set)	Payment in Kind	Grain for Family	Grain Sale			
Objective function	-	-	-		+	-		-	-	-					+		≤	1
Machinery ownership	+																≤	0
Land preparation capacity in hectares	-			+	+	-											≤	0
Crop establishment capacity in hecates	-						+										≤	0
Reaping capacity in hectares	-					-					+						≤	0
Threshing capacity in hectare	-				+	-						+					≤	0
Manual labour by period				+	+		+	-			+	+					≤	+
Operator labour by period				+	+		+		-		+	+					≤	+
Long term loan	+	-															≤	0
Cash (by period)			-	+	-	+	+	+	+	+	+	+			-		≤	+
Land				+													≤	+
Land for crop establishment				-			+										≤	0
Inputs application (by period)				+			+			-							≤	0
Crop for reaping							-				+						≤	0
Crop for threshing											-	+					≤	0
Yield												-	+	+	+		≤	0

Figure 3. Schematic of Model Matrix.

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