DEVELOPMENT AND APPLICATION OF AN
OPTIMUM MACHINERY COMPLEMENT
SELECTION SYSTEM

By

STEVEN CURTIS GRIFFIN

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Thesis Approved:

Daniel D. Kletke

Thesis Advisor

Odell L. Walker

Donald W. Grace

Norman N Durham

Dean of the Graduate College

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CHAPTER I

INTRODUCTION TO THE STUDY

Farm Machinery in Agriculture

The development and adoption of farm machine technology in the U.S. agriculture during the past 40 years has had a significant impact on the structure of agriculture and brought on substantial change in the nature of farming. Expanding farm size, increasing capitalization, and growing dependence on nonfarm inputs characterize today's modern farm, which is now so dramatically different from the small, self-sustaining unit of years past. The net effect of these changes is that farming and farm management have been transformed from a craft and a way of life to a commercial business requiring the discipline and tools of modern business management.

The Changing Structure of Agriculture

An examination of the shifting economic composition of the farming sector provides insight into the changes taking place in production agriculture. Between the years 1960 and 1977, total farm numbers declined 31.7 percent (USDA, 1978b). During the same interim, however, the number of farms having cash receipts more than $40,000 (Class I and above) increased 351 percent. These larger "commercial" farms in 1977 represented 18.8 percent of the total number of farms and marketed 78.1

percent of total farm output, compared to only 2.9 percent of the farms and 32.8 percent of production in 1960.

At the other end of the economic continum, farms with less than $5,000 in sales, representing 62.2 percent of all farms in 1960, declined to 46.5 percent of all farms (USDA, 1978b). This change represents an exit from the farming industry (or, for a few, an expansion in size) of 1.3 million farms in only 17 years. Thus, 96 percent of the decline in farm numbers between 1960 and 1977 can be attributed to the demise and dismemberment of these "small" farms.

The obvious mathematical results, and indeed, the economic propellant of such a decline in farm numbers (with only a slight decrease in the land area devoted to farming) is an increase in the average farm size (in terms of acres per unit). The average farm size in the United States has increased from 213 acres in 1950 to 393 acres in 1977 (USDA, 1978a).[1] Oklahoma agriculture has followed approximately the same trend. Oklahoma's average farm size was 252 acres per farm in 1950. It expanded to 434 acres per farm in 1969 (Collins and Ray, 1975).

The Changing Input Mix of Agricultural Production

As the structure of the farming industry has evolved from a large number of small farms to a much smaller number of relatively large farms, the combination of inputs used per unit of agricultural output has also changed greatly (Table 1). Machinery, for one has been used extensively by farmers to replace labor in the input mix, allowing farmers to stretch their own labor over more acres and activities. The availability of ever-larger farm machines and the substantial economies of scale involved

Table 1. Indices of Crop Production Per Acre, Selected Major Farm Inputs, Number of Tractors and Total Horsepower, United States, Selected Years, 1950-78

Year	Crop Production Per Acre	Total Input	Farm Labor	Cropland Used For Crops	Mechanical Power and Machinery	Fertilizer, Liming, Materials & Pesticides	Number of Tractors	Total Horsepower of Tractors
				Index 1967 = 100			thousands	millions
1950	69	104	218	111	84	29	3,394	93
1955	74	105	185	111	97	39	4,345	126
1960	89	101	141	104	97	49	4,688	153
1965	100	98	110	99	94	75	4,787	176
1966	97	98	103	98	96	85	4,783	182
1967	100	100	100	100	100	100	4,786	189
1968	105	100	96	98	101	105	4,766	195
1969	106	99	93	98	101	111	4,712	199
1970	104	100	88	98	100	115	4,619	203
1971	112	100	86	100	102	124	4,584	206
1972	115	100	81	98	101	131	4,549	209
1973	116	101	80	103	105	136	4,518	212
1974	104	100	78	106	109	140	4,493	219
1975	112	100	75	108	113	127	4,469	222
1976	111	102	72	109	115	145	4,434	228
1977	116	103	70	111	116	151	4,402	232
1978	na	na	na	na	na	na	4,370	238

source: (U.S. Department of Agriculture, 1978b).

na: not available

in their use has both allowed and encouraged many "family" farms to take part in the general increase in farm size.

In 1940 farmers owned \$1.8 billion worth of tractors and other farm equipment and used 20.5 billion hours of labor (Table 2). Thus, machinery assets per hour of labor in that year averaged nine cents. By 1977 machinery investment per hour of labor averaged \$12.32 as farmers purchased over \$9.4 billion in farm equipment and machinery and employed about 4.7 billion hours of labor.[2]

The capital required for machinery investment continues to be the largest non-real estate use of capital found on the balance sheet of the farming sector (USDA, 1978c). As an annual user of funds, machinery purchases in 1978 accounted for 54 percent of new capital formation and 12 percent of the total cash flow on farms (USDA, 1978c). Also, the proportion of the average farmer's capital assets "tied-up" in machinery has tended to increase, in real terms, since mass farm mechanization swept the agricultural production sector during the post-World War II years. Farmers spent \$7.76 billion in 1977 for tractors and other farm machinery (excluding trucks and automobiles); pushing the total value on farms to more than \$62.1 billion (USDA, 1978c). This represents an average machinery investment of \$21,391 per farm.

The almost constant stream of scientific discoveries, innovations, and technological improvements has presented farmers the opportunity to employ new, more efficient means of increasing their output at lower unit cost. But, many of these technological developments would be of limited value to farmers without the proper equipment to prepare the land, apply the production inputs, and harvest the output in a timely manner. Thus, both directly and indirectly, the input of machinery

Table 2. Value of Tractors and Other Farm Machinery on Farms, Hours of Farm Work, and Machinery Investment Per Hour of Labor, United States, Selected Years, 1940-78

Year	Value of Tractors and Other Machinery on Farms	Hours of Farm Work	Machinery Investment Per Hour of Labor
	(million dollars)	(billion hours)	(dollars)
1940	1,840	20.5	.09
1950	8,407	15.1	.56
1960	15,503	9.8	1.58
1970	24,753	5.9	4.20
1971	26,158	5.7	4.59
1972	27,988	5.4	5.18
1973	30,008	5.3	5.66
1974	34,912	5.2	6.71
1975	44,764	5.0	8.95
1976	53,171	4.8	11.08
1977	57,885	4.7	12.32
1978	62,088	na	na

source: USDA, 1978d. (U.S. Department of Agriculture, 1978b)

na: not available

services is assuming a larger and more important role in the agricultural production process.

Farm Machinery Capacity and Use Over Time

The inventory of major farm machines on farms (in number of individual units) has risen rapidly in the past to meet the growing demand. By 1957 there was an average of one tractor per farm in the United States. The estimated number per farm rose to 1.6 tractors by 1970. In recent years, however, the trend toward greater numbers of farm equipment has leveled out as fewer units of larger-sized machines are providing the necessary capacity (USDA, 1978b). The average horsepower of tractors on farms, for instance, has been increasing rapidly (more than 3 percent per year). The average PTO horsepower of farm tractors sold in 1977 was 105, compared with 63 in 1965, only 12 years earlier (USDA, 1978d). While only four percent of the farm tractors sold in 1963 were rated 90 horsepower or more, 44 percent of the tractors sold in 1963 were rated 90 horsepower or more. The average amount of tractor-horsepower available per acre nationwide has increased more than 600 percent since 1940 and 150 percent since 1960 (Table 3). In a 1974 survey, Oklahoma commercial farmers owned an average of 2.2 tractors of an average 67.5 horsepower, providing approximately 156 horsepower hours per crop acre (Micheel and Krenz, 1976).

The Farmer's Efficiency Dilemma

In adjusting to the changes and managerial challenges of farming, farmers have had to purchase more of their inputs from nonfarm sources, and there by increased their vulnerability to off-farm influences, and

Table 3. Number of Acres and Tractors Per Farm, Average Horsepower Per Tractor and Per Acre, United States, Selected Years, 1940-77

Year	Average Number of Acres per Farm	Average Number of Tractors per Farm	Average Horsepower per Tractor	Average Horsepower per Acre[a]
	(acres)	(tractors)	(horsepower)	(horsepower)
1940	167	.25	22.3	.0330
1950	213	.60	27.4	.0773
1960	297	1.18	32.6	.1300
1970	373	1.56	43.9	.1842
1971	377	1.57	45.2	.1878
1972	381	1.56	46.8	.1911
1973	383	1.54	48.3	.1946
1974	384	1.54	50.0	.1949
1975	387	1.52	52.1	.2017
1976	390	1.60	51.4	.2096
1977	393	1.59	52.7	.2225

[a]Standing horsepower only and thus does not reflect intensity of use.

source: U.S. Department of Agriculture (1978b).

lessened their ability to weather periods of low returns. Since 1950, total cash expenditures by farmers have taken upwards of 73 percent of total farm cash receipts, reaching 83 percent in 1971 before declining as farmers experienced usually favorable receipts (Tweeten, 1975). However, even as farmers emerge from their greatest prosperity ever (1973-74) the prospect for a recurrence of a new "cost-price" squeeze weighs heavy on the farm economic horizon, as inflation continues to raise cash costs and a less-favorable supply-demand balance looks to depress or barely maintain farm receipts.

The competitive economic structure of production agriculture forces farmers onto an economic treadmill of ever-increasing speed.[3] A farmer must constantly "run" (i.e., improve his economic efficiency) faster to merely maintain his standard of living. Proper machinery selection and management represents one challenge and opportunity to increase farm productivity.

The Problem

Despite glowing testimonials to farm machinery adoption and use by American farmers, many farmers have difficulty in finding the "right" machinery combination that provides the necessary level of machinery services for their farm business. Agriculture financiers accuse mismanagement of farm machinery acquisition and use as a major culprit in farm business failures (Brown, 1968). Farm management specialists point out that while some farms are seemingly over-mechanized, others are well under-mechanized. Both situations prevent optimum returns, and in some cases, even jeopardize firm survival.

Machinery-related expenses, such as fuel, hired labor, and repairs, may also constitute as much as 35 to 50 percent of an individual farm's operating expenses (LePori and Stapleton, 1967). Machinery investment varies with the size and type of farm, but can represent upwards of 18 percent of the total assets (including land) on farms (Waters and Daum, 1974).[4] Therefore, it would seem that substantial savings and increased productive efficiency could be obtained with better selection and allocation of power and machinery systems by farmers. Yet, machinery selection decisions, whether for a complete complement or single machine, are generally made so infrequently and involve such complexity that a farmer's unaided experience in selecting his farm equipment may prove to be of limited, if not dubious value. A less than optimal selection decision can burden the efficiency and inflate the costs of an entire machinery complement throughout the life of the poorly selected machine, or machinery system. Furthermore, due to the selected machine's presence as a fixed asset having a relatively low reservation price, in subsequent, even optimal, selection decisions, the costly effects of a poor selection decision may well outlast the machine's own operational life.

The task of taking various farm machines and blending them into an efficient, productive system is not an easy one. Machinery alternatives, either for addition or deletion from a farmer's machinery complement, may vary in age as much as 10 to 15 years. Some machines serving in the machinery "pool" may have been purchased for an entirely different function or crop tillage system. Since most agricultural production requiring field machinery is seasonal, equipment will necessarily have high and low periods of usage and, quite probably, stand idle much of the time. Part of the machines in the system may not even be owned or operated by the farmer, but whose services are contracted from custom operators.

Noncontinuous tillage systems (e.g., moldboard plowing every third year,) noncontinuous tillage requirements (e.g., two discing operation separated by some time lapse but still within the same crop year) and systems using selective chemical application and other controls on a "need" or threshold basis, also complicate the farmer's machinery selection decision as well as other production input decisions.

While it is unusual for farmers to purchase all of the machines necessary for their farming system at one time, it is also unusual for a machinery investment decision to be exclusively associated with a single farm machine. Instead, the selection decision for even a single addition or replacement inevitably determines, at least in part, the feasibility and economic flexibility of a much wider investment plan involving the entire farm machinery system. Clearly, the interrelationships, both in terms of technical compatibility and practical operation, suggests a complex situation calling for detailed analysis.

One of the most prominent examples of the interrelationships involved in farm machinery selection is embodied in the farmer's choice of a tractor. The tractor is the most important item of a farm machinery complement, both in terms of the dollar investment it individually represents and by the key role it plays in determining the size and composition of the complement to which it provides locomotion and power. The tractor's predominance, though dimmed slightly by emerging numbers of self-propelled, primarily harvesting, equipment, is based on its role as a shared power source. In general, a shift to larger farm equipment generally must be preceded, if not accompanied, with an increase in tractor power. By the same token, under-sized implements when matched with a larger-than-necessary tractor may waste fuel, power, labor, and precious investment capital. Therefore, decisions concerning the tractor or any of its implements, either singularly or as operational groups, invariably affects the operation and economics of the entire system.

The trade-off between labor-intensive operations and machinery-intensive operations is also difficult for the farmer to analyze, but plays a very important role in a farmer's choice of machinery. Labor availability is undeniably a problem in agriculture. Traditional wage rates are low relative to other segments of the economy. In addition, most farmers need only seasonal help while most laborers prefer year-round employment. Depending upon the amount of other "productive" chores, the effective wage rate for a farm laborer, for example, earning $10,000 per year (2400 hours maximum) can vary between $4.17 (fully employed) and $12.50 (assuming 800 hours of productive labor per year) and higher. The optimal machinery complements in the above range would be substantially different from the one using the more typical farm wage rate (in Oklahoma) of approximately $2.50 per hour.[5]

Finally, a characteristic that is widely recognized but difficult to analyze is the need for timely operations. Farmers recognize that various fieldwork operations such as seedbed preparation and planting, require completion within certain time periods to avoid potential yield losses as a result of seasonal weather conditions and(or) an insufficient number of growing days. While certain operations should be undertaken during fairly riged time periods to comply with optimal production practices, other operations are economically much more flexible in terms of their relative starting and completion dates. Due to the significant influence of weather on crop and field conditions and its uncertain nature, there is an additional trade-off decision between the certaintly of timely operations and its related benefits and the cost of insuring timeliness with increased machinery capacity.

The coming of age and acceptance of the "big" tractor (i.e., tractors rated at 140 horsepower and over) and associated equipment has provided an almost infite myriad of alternative sizes and combination to solve a farmer's particular farm machinery requirements.[6] Tractors rated at over 500 horsepower are in the market development state of production. Tractors, ranging in size at "appropriate" increments from 30 to 300 horsepower, are now currently available; adding to the opportunity as well as to the confusion.

Available Farm Machinery Decision Aids

The value of many of the conventional decision aids currently available to farmers have unfortunately succumbed to the vicissitudes of the times. The recent experience with double digit inflation, spiraling interest rates, quadrupling energy prices and input shortages of all types has rendered highly suspect many time-tested rules-of-thumb used by farmers in their machinery selection decisions. Guidelines, for example, based on abundant $2.50/hour labor, or relatively cheap fuel, or on the largest available tractor being rated at 125 horsepower or less, have been made convincingly obsolete. Even newly published machinery handbooks are sadly lacking in scope as a result of general inflation and the recent quantum jump in machinery purchase prices and repair costs,[7] causing farmers to use dangerously extrapolated trendlines.[8] Farmers are also faced with an advancing farm machinery technology producing a new generation of tractors, and implement sizes and designs unaccounted for in past farm machinery studies and current decision aids.

Many decision aids, including some widely disseminated computer programs, require such static and simplifying assumptions that their "answers" are far removed from the real world "questions", and thus, of limited practical value. Other systems can provide "answers" in terms of dual wheels, alternative power sources, tillage speeds, etc., but "the man who needs a 29.5 horsepower tractor (as the procedure might determine) still has to choose between the (available) 37 and 45 horsepower model" (Candler, 1968). Obviously, the only real help provided the farmer in his selection decision in this case is perhaps a more mathmatical rephrasing of the original question. Certainly, an "answer" recommending dual wheels is of limited use if one still does not know which tractor to buy and put them on!

Machinery Information Sources

Farmers make their machinery decisions on the basis of a variety of information sources. One primary source of information may be the local machinery dealer; probably well-informed but of, perhaps, questionable objectivity. Next might be the neighbor who perhaps just recently purchased the equipment the farmer "has his eye on". Farm industry publications and agricultural extension fact sheets are other sources. All of these sources provide a variety of, but many times outdated, inconsistent, or otherwise biased "rules-of-thumb" to "average" farm "needs" from which a farmer must try to mold a machinery complement feasible to his uniquely particular needs. Certainly the farmer can add his own experience, though it is sometimes hard to determine what really made things work well or badly (whichever the case may be). The farmer is also hampered since machinery selection is a complex problem very much unlike any other farm input (e.g., farm machinery is durable over several production cycles whereas one starts clean every year with inputs like fertilizer or seed).

The computational difficulty involved with machinery selection cannot be easily minimized. Though machinery cost equations have been developed (to compensate for the usual lack of complete and detailed records) with computational ease as a major objective (many times to the detriment of expected accuracy), even these procedures are tedious and time-comsuming, at best. More sophisticated mathematical techniques are very time-consuming, if not impossible, to do by hand or simple calculator. Also, as the machinery selection problem reaches a problematic size of realistic proportion, the possibilities for computational and clerical error rise significantly. The volume of data required is also quite large and presents a major problem of maintaining a complete and up-to-date machinery information data bank. Fortunately, the electronic computer is admirable suited with proper programming for these kinds of computational and data access problems.

Farmers also need a greater understanding of scientific management techniques and improved analytical skills (at least indirectly through the use of computerized management services) in order to make better decisions regarding farm machinery use. Records of the farmer's own performances are seldom available, so technical data must be synthesized, or otherwise made available, for the farmer's own machines and selected alternatives. Farmers often cannot specify their objectives or restrictions under which they operate or want to operate. Decision models for analyzing machinery systems must provide, in these cases, a logical problematic structure, if for nothing more than outlining for the farmer the appropriate questions and considerations.

The Existential Situation

The Oklahoma crop farmer does not have available to him, either directly or indirectly through management services, a practical, understandable, and economically sound machinery selection model to update, advise and guide him in his machinery management decisions. Nor, for that matter, does the farm management specialist and production economist currently have a selection system that can provide farm machinery "answers" to representative farm situations from which more general guidelines can be induced and then communicated to farmers, farm machinery manufacturers, and other interested parties.

As the resource base and resource demands of the farm firm continue to change, as components of existing machinery systems need replacement or up grading, as machinery-related technologies break new ground and provide new economic alternatives, there is a serious need for continuing managerial assistance, improved analytical tools and research quantitative knowledge of optimum farm machinery complements. Machinery selection is the first of a chain of machinery management decisions which can lead to profit or loss from all or part of the farm enterprise. Furthermore, deciding which machines to use involves fundamentally a comparison of crop-production methods.

A Working Hypothesis

A computerized decision aid, capable of identifying optimum machinery complements within the decision space faced by the farmer,[9] would be of real assistance to the farmer in performing his most vital economic function: providing abundant food and fiber at maximum economic efficiency and the lowest possible cost to the consumer.

A knowledge of optimally-selected farm machinery systems, their associated cost functions, and how their composition and cost structure vary with alternative farm sizes, tillage systems, wage-capital ratios, or timeliness risk-preference, would also be valuable to equipment dealers and manufacturers. Such knowledge would help in sales campaigns, controlling regional inventories, and more importantly, matching new and future machinery production to the true mechanical needs of production agriculture.

Agricultural lenders would find this type of analysis valuable in financial consultations with their farming or farm machinery-related customers as they strive to serve agriculture's credit needs.

Internal economies of scale come about largely through the more complete utilization of "lumpy" factors of production, machinery being the classical example. The determination and study of optimally selected machinery complements would provide valuable insight into a major source of economies of scale found in production agriculture. From the public viewpoint, it is desirable to know the size of farm which would result in the most economical production of farm products. The farmer is also concerned with adjustments he can make in farm size to affect the efficiency and net income of his farm.

In corporation of an optimal machinery complement selection model, either reactively or simultaneously, into a large-scale farm management study migh well predict the behavior and growth of farms more accurately and provide more efficient plans for their resource use. The impacts of alternative agricultural energy policies, environmental controls (e.g., requiring additional mechanical control to substitute for a banned herbicide), tax code revisions (especially those involving investment tax credits, depreciation write-offs, etc.), and minimum wage laws for agricultural workers, might also be analyzed more throughly as a result. Certainly, better insights into the public policy needs of production agriculture would be provided to policy makers as the specification error is reduced in farm behavior estimates and a better understanding of the decision-making process in farm resource use is provided.

Lastly, better cost estimates resulting from optimally selected machinery complements and optimally-scheduled machinery use (with respect to timeliness) would enable better evaluation of new technologies in which the "input package" has assumed particular importance or involves a retolling of farm machinery inventories (e.g., "minimum" or "no-till" tillage versus conventional tillage; or, narrow-row cropping versus the wider row methods).

Review of Literature

Considerable research has been done and much has been written by agricultural economists and engineers in the area of farm machinery costs and performance. Numerous studies have dealt almost exclusively with machinery cost analysis and the identification of predictive cost coefficients and parameters. The work of Larson (1955), Hunt (1964), Bowers (1970), and others in isolating these cost components and deriving procedures for their calculation is well known. Many state agricultural experiment stations, state extension services, and some commodity organizations have, both separately and cooperatively, surveyed and reported current machinery costs for their respective audiences. Since these cost estimation procedures are widely distributed and elementary to the general topic, a detailed rendition of the various equations, coefficient tables, and procedures will not be attempted here. The reader is directed to the Agricultural Engineer's Yearbook (ASAE, 1973) or other machinery management publication for reference should such a basic orientation be needed.

Machinery Selection Studies

Attempts to develop systematic procedures to solve the problem of efficient farm machinery selection can be found as early as 1934 (Carter). Since that time, several different analytical procedures have been formulated, adapted, and expolored for use in analyzing farm machinery management problems. These methods can be broadly classified into several distinct approaches. For purposes of this review, we will look at representative works and focus on their particular contribution in each of the following procedural categories:

1. Computerized Least-Cost Comparison and Search (sometimes referred to as "Step-by-Step" Estimation).
2. Budget (synthetic, engineering, or envelope curve) Approach.
3. Systems Simulation.
4. Mathematical Programming (including conventional simplex accompanied with partial budgeting, dynamic programming, and mixed integer programming).

Least-Cost Comparison and Search Techniques

The efficient selection of farm machinery is a long and tedious operation, at best. It is not surprising that the electronic computer, with its ability to perform thousands of mathematical and logical operations per second, was quickly adapted for use in solving machinery management problems. Simons (1962) was among the first to utilize the computer for machinery cost analysis and equipment selection with stored computer programs. Using an IBM 650 computer and the SOAP (Symbolic Optimum Assembly Program) programming language, he coded two programs for generalized use. One of the programs was used to calculate the annual field machinery costs for operations where the number and type of machines were known. The other program was used to make efficient selections of field machinery for operations where the types of implements desired and acreages to be covered were known. Simons used both timeliness discount equations and alloted time considerations in developing his least-cost selection algorithm.

Hunt (1967) updated the techniques used by Simons in a computer program which determined tractor power levels and the size of accompanying farm equipment by minimizing an annual cost equation through an iterative "step-by-step estimation" process. The 1967 Hunt procedure made use of several simplifying assumptions and(or) limitations. The most significant are as follows:

1. Implement size and tractor horsepower are assumed purchased on an infinitely divisible, and constant dollar per foot of width or PTO horsepower basis.

2. The minimum number of power units in the maximum sizes allowed are always selected. (The model is actually solved only for the total horsepower required.)

3. Implements are selected both for size and number, but not necessarily to conform with limitations created by the tractor sizes selected.

4. Timeliness considerations are introduced by means of a single linear function of penalties (in dollars per hour of delay).

5. Machinery operations are considered to be in sequential, mutually exclusive, and independent time periods with respect to sharing the available tractor power.

Hunt (1972) later added to the program a more precise and dynamic mathematical model for tractor performance, thereby providing an "optimal" travel speed for each operation, as well as the "correct" machine sizes. Unfortunately, as Hunt notes, the tractor and implement sizes selected by the program did not conform to typical equipment found on surveyed farms. The Hunt program did, however, serve as the springboard for a generation of machinery selection models, especially among agricultural engineers.

Schmeidler (1973) for example, took the Hunt (1967) program, revised it in several ways, and made one major modification. The revisions included: expanding the problematic capacity of the model, providing an internal algorithm for determining a "good" start point (for subsequent iterations), improving the efficiency of the iteration procedures, and increasing the flexibility of the data input. The model was modified to allow for the "optimal" selection of alternative fuel types. This addition complicated the optimization of the annual cost equation from one implicityly using differential calculus (as in the orginal model) to one necessitating an elaborate search procedure.

Scarborough and Hunt (1973) modified the Hunt (1967) program by including algorithms for determining the optimum replacement periods for equipment (in the original model, the user directly inputs the life of the machine) and for scheduling operations which were competitive in nature (i.e., partially lifting assumption 5 as previously discussed). The scheduling modification was accomplished by allowing the user to arbitrarily (or experimentally) segregate the machinery operations into several (up to three) power classifications. Within each classification, conflicts for the power source are resolved by considering the timeliness costs of competing operations on a day-to-day basis and giving priority to the operation which would suffer the greatest economic loss.

Osborn and Barrick (1970) developed a computer model (TESP) to select a least-cost machinery complement in which selections were based on three factors: technical feasibility, time requirements, and annual costs. Basically, the TESP solution algorithm starts with the widest implement and the smallest tractor and tests whether they are technically feasible (according to draft and speed parameters) to perform the specified operation. If not, the routine selects the next size, and so on, until the tractor and machinery complement meet the predetermined specifications. The total variable costs for the operations specified are then summed for each technically feasible machinery complex. The investment requirements and the total annual costs for each machinery complement are calculated and the current least-cost solution updated.

The Osborn-Barrick model provided an alternative to the infinitely divisible machinery sizes assumed in the Hunt models. The Osborn-Barrick program can select from as many as 45 tractors (with up to 10 different speeds each) and 20 types of implements with up to 8 different widths each. Therefore, the "answer" is always in terms of farmer-available equipment and in sizes (and purchase prices) that actually exist. The model does, however, still carry the assumption that each different type of operation is performed in one (and only one) mutually exclusive time period. Also, the completeness of the search procedure in the multi-tractor case is not rigorously established as to whether the procedure's least-cost solution is a global optimum.

Griffin (1973) programmed a one-tractor optimum machinery complement selection procedure for a study by Reinschmiedt (1973). Like the Osborn-Barrick model, this procedure is combinatorial among actual avaialble-to-the-farmer machinery alternatives. However, unlike the TESP and other previously discussed programs, the Griffin-Kletke model allows for the tillage requirements for a particular farm enterprise mix to be divided or combined into as many as 24 mutually exclusive time periods (each representing, say, one-half month of time), each with its own timeliness (i.e., hours available for farm work) constraint. Operational requirements of particular implement type can appear in any number of these time slots, possible competing in each with a different combination of other required functions for the shared power source.

The Griffin-Kletke algorithm utilizes the least-cost comparison and partial budgeting techniques generally followed by other combinatorial programs. The relative superiority of one size or model of a particular implement type over another, when no tractor change is needed, depends on the economic trade-off between initially higher investment, but greater capacity machinery, and generally lower investment, smaller capacity implements. The larger capacity machinery, requiring fewer hours of labor and tractor operating time, brings economic benefit if the total operational cost is reduced enough to offset the generally higher ownership costs. The smaller capacity implement will benefit from the lower investment and associated ownership costs, but may face significantly greater operational expense per acre than the larger capacity machine.

The decision criteria for selecting machines in which tractor size must be incremented differs in that the increased ownership costs of the larger tractor cannot be distributed and analyzed on an hourly decision basis (i.e., marginal cost basis) until the total hours of annual use are known (so that the fixed cost can be properly allocated). In the one-tractor environment, however, total complement costs of alternative configurations (since they are relatively few in number) can be quickly computed and compared to find the least-cost solution and global optimum.

The search procedure is greatly simplified by the economic question posed being one of "which tractor or implement to buy?" rather than the vastly more complex question of "whether to buy or not?" implicit in a multiple unit selection problem.

Cost Budgeting Studies

Classical economic theory indicates that short-run average total cost curves can be constructed, for a given plant size, by varying the amount of product processed by the plant. An analogy can be drawn between a farm machine (or system of farm machines) and a plant processing a product. In this case, the product is a portfolio of desired tillage operations to be performed by the machines. By calculating a series of short-run (i.e., the plant size is fixed) cost curves, joining them by an "envelope" or long-run (i.e., the plant size may vary) average cost curve, the desired plant size, or in this case, te optimum machinery complement can be determined by identifying on the long-run average cost schedule the least-cost plant size for the neccessary capacity (Leftwich, 1970) (Figure 1).[10]

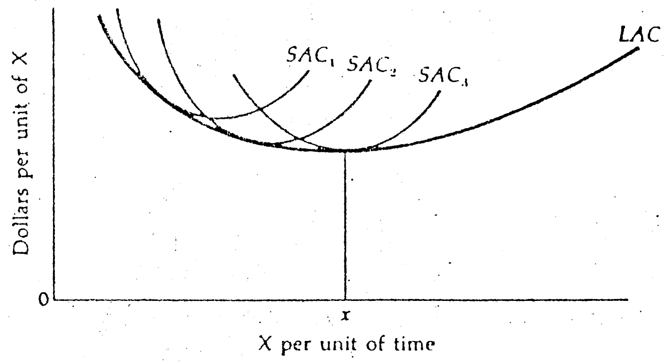

Figure 1. Short-Run and Long-Run Average Cost Curves

The primary drawback of these studies is their use of a limited number of rather arbitrarily constructed machinery complements, or "plants" (to continue the analogy), from which the long-run cost curve is dervied. These arbitrarily constructed machinery complements invariably lack "imagination" (i.e., they cannot answer rigorously negatively the question whether a "better" machinery organization exists in a particular neighborhood of operational requirements) since they inevitably limit the full range of possible machinery complement formulations. One example of this lack of imagination which is quite commonplace is these types of studies is where the alternative complements constructed for analysis involve only full-size implements (i.e., the largest implement size normally associated with or pullable with a certain size tractor). The result is an inflated average cost curve if some of the full-size capacity could be replaced by cheaper, smaller units (e.g., if one has a large tractor and a little plowing to be done, it is not always cost-efficient to buy the largest plow pullable by the tractor).

By simplifying the machinery selection problem inot one of selecting among alternative complements rather than constructing a complement from among alternative machines, substantial error may be introduced to upward bias the analysis. The derived long-run average cost curve or "envelope" curve (from which one would determine his "optimum" machinery complement by locating his particular farm size on the horizontal axis and the short-run average cost curve producing the envelope's boundary at that particular farm size) is not necessarily the "best" or least-cost (i.e., on the efficiency frontier) since each of the "plants" used to derive the short-run average cost curves is not satisfactorily proven to be a least-cost combination.

In a study by Ihren and Heady (1964), for example, five complements were constructed using one and two tractor combinations of two and three-bottom plow tractor sizes and associated (full-sized) equipment. Even with this relatively limited set of combinations the two two-bottom plow tractor complement was never found to be the most efficient combination over the entire range of farm sizes studied. One can only wonder whether the construction of a sixth complement might invalidtate the "efficiency" of the other four complements.

On the other hand, this type of analysis has strong theoretical appeal and is conceptually quite simple, though somewhat tedious and time-consuming to apply without computer programming. Also this procedure is possibly more adapted to discovering the relative extent of potential economics of scale in farm machinery, though it is difficult to infer how accurately, rather than the selection management use of a farm machinery complement for an individual farm situation or farm size.

Systems Simulation Studies

Groenewald (1967) chose a systems simulation approach for selection of machinery combinations in crop production on Corn Belt farms. Reasons cited for this approach were (1) the desire to incorporate necessary curvilinear relationships,(2) the desire to obtain profit maximizing (rather than minimizing cost) solutions, and (3) difficulty in obtaining integer solutions to linear programming formulations of the problem. The practical value of the model was limited (according to Groenewald) by allowing the presence of only one crop,assuming no fixed assets in machinery, and permitting only "new" machines to be purchased.

Kizer (1974) augmented the machinery management potential of the Hutton-Hinman farm simulator (Hutton and Hinman, 1969) to emphasize and analyze machinery management problems. A farm situation (defined in terms of an exhaustive list of petinent parameters) is inputed and dynamically simulated for a defined time horizon. Machinery management "problems" associated with different sizes of machinery systems are analyzed by simulating each system, and then comparing the results. Labor and management income is generally used as the decision-making criterion, though other factors may also be used. By experimenting with different machinery systems the farmer can purportedly use the derived information to improve upon his acquired or native intuitive ability in arriving at an appropriate plan. While the model has great "hands-on" appeal and problem flexibility it is also nonoptimizing and, therefore, must be augmented with a great deal of imagination, patience and computer time to provide even "good" solutions.

Studies Using Mathematical Programming

Ambrosius (1970) used a dynamic programming technique to solve optimal replacement and machinery investment decisions under alternative firm growth in farm size, timing of growth and farmer's risk preference were programmed and analyzed. The study proclaimed that growth in the farm size was a much more important factor in replacement decisions than machinery age and that the timing of tractor and combine replacement closely paralleled land acquisitions. It was found to be more economical to buy one (or more) large tractor(s) (or combine) than two (or more) small ones. Also, the economic loss from overinvesting in machinery (relative to the optimal solution) was found to be small relative to that which is likely to result from undersized machinery. This finding was logically expanded (though rather weakly) to say that farmers should initially buy machinery capacity, up to their expected farm requirements of five years (half of the ten-year planning horizon used in the study) in the future. Otherwise, the best strategy is to initially buy machinery just sufficient for the current acreage, then replace this machinery for larger equipment at the time the farm is enlarged. Optimal solutions were found to be highly insensitive to replacement timing but highly sensitive to increasing labor costs.

Conventional Simplex with Partial Budgeting

Armstrong and Faris (1964) used a simplex linear programming model with post-solution partial budgeting to determine their "optimum" complements. In the California study, the researchers used the observation that the lowest cost per acre was "always" obtained when the largest implement normally associated with a certain size of tractor is used with it (in other implements not necessarily limited by tractor size, e.g., row planters, they limited themselves to sizes commonly found on farms) to formulate "optimum" machinery systems.[11] Several alternative systems were constructed and then incorporated into a cost-minimizing LP tableau with the model constrained by time limits on the various machinery operations. Solving the model with a conventional simplex algorithm, a continous "optimal" solution was found in decimals of the defined systems. Partial budgeting (from the points of the fractional solution to integer solutions) was then used to determine which of the nearest integer solutions constituted the lowest cost system. The assumption that the "optimal" integer point would be one of the nearest "corners" to the continuous optinal was acknowledged as a serious weakness in the procedures. The authors pointed to the need for an integer programming solution method to overcome it.

Mixed Integer Programming

Vogt (1967) formulated a mixed integer programming model to determine the effects of machinery purchase alternatives on optimal production plans of typical Missouri farms. Activities to purchase a larger tractor with associated equipment and self-propelled combine were required to be at integer values if basic to the solution. The programming matrix consisted of 38 equations and 34 real activities (two of which were for machinery purchases) and allowed for several crop growing activities (e.g., corn, soybeans, wheat, and meadow), several livestock activities (e.g., beef cows, feeder calf, and yearly steers) and several purchasing activities (e.g., additional capital, land, labor, and livestock production facilities). A mixed integer programming routine by Hurt (1964) was used to s solve the model.

Rounding error involved in the solution procedure and a more general (though not related) problem of solution convergence (before exceeding the storage limitations of the computer) were cited as major problems limiting the problemative size and complexity of the study.

Acton (1970) also chose a mixed integer formulation to determine farm investment decisions due to the promise of a mathematically rigorous "optimal" solution provided by the technique. Acton saw integer programming as a satisfactory framework for conceptualizing and handling farm investment problems (at least under conditions of certainty). However, like Vogt, Acton was limited in the number of integer activities by his computer package. In the study, he simplified the machiner selection decision into one of choosing between several exogenously defined machinery "systems," as had Vogt and others, to conserve the limited number integer activities available in his solution algorithm.

Summary of Literature Review

From this review, it is obvious that scientific machinery selection procedures have ventured a long way since Carter and 1934. With the harnessing of the computer, several modeling frameworks have been developed (not all of which were reviewed here).[12] Successive studies have, for the most part, attempted to remedy what was felt to be the more blatant simplifications of past studies. In many cases, the state-of-the-arts in machinery selection has moved ahead only as fast as improvements in computer technology became available. As computers increased in size and speed, and better programming languages and alorithms were developed, machinery selection procedures were expanded to take on more realism and rigor in solving machinery problems. However, while economic theorists have exhorted the farmer to maximize his objective function and equate marginal productivities of resources, the practioneer and consulting scientist have been, for the most part, relatively content to suggest changes which may only be a little better than past practices. Acton (1970) traces the inadequacy to the theorist's unwillingness or inability to analyze problems involving discontinuity and uncertainty, and the practioneer's understandable willingness to settle for a feasible plan rather than an optimal one.

Also clear in the studies reviewed was the recurring theme and general consensus that the best formulation of the machinery selection problem is in terms of a mixed integer linear programming (MIP) model. While some researchers sought to develop other procedures and substitutes (mostly after disparing at the lack of suitable MIP-solving computer software), others made valiant, but frustratedly limited efforts with the MIP algorithms availabe to them. Morris (1965) laments some of the frustration generated by attempting to use or develop improved MIP algorithms in his review of operational research techniques in agricultural applications.

The failure of previous studies to find a workable (and cheaply solvable) mixed integer programming (MIP) formulation encouraged the further development of computer utilizing nonoptimizing systems simulation, least-cost comparison, and systematic search techniques. Unfortunately, simulators are generally so hand-crafted and narrow in the exact form of their first application that their usefulness as a general farm management tool is less than adequate. The rigor of their optimality premise in least-cost comparison and search techniques is questionable (or, at least narrowly defined), especially in problems considering multiple tractor and configurations. Also, due to the combinatorial nature of machinery complement possibilities when multiple units are allowed, an explicit and complete enumeration of possible complements (as is represented to be done by some of the reviewed techniques) becomes prohibitively time-consuming for problems of even modest size.

A selection problem, for example, involving eight types of machinery (including tractor), up to seven sizes in each category (but only 42 total), and allowing up to three machines from any one category (e.g., three 95 horsepower tractors, or one 95 horsepower tractor and two 130 horsepower tractors) would involve creation of over 1.7 billion possible complements. To appreciate the magnitude of this number, consider that if a computer could systematically creat a complement and calculate its performance and costs at the rate of one complement per second (an exaggerated impossibility), hour after hour, year in-year out (another impossibility), the search would take approximately 540 years to complete. Clearly, if a mathematically rigorous, optimum solution is desired, a more efficient algorithm is required.

In 1970, International Business Machines Corporation (IBM) introduced a program product known as MPSX (Mathematical Programming Systems Extended), providing expanded capabilities over its predecessor, IBM's MPS/360 (IBM, 1973). One extension of the new IBM system was the availability of a mixed integer programming (MIP) system, providing the ability to solve large-scale mixed integer, linear programming problems with computational efficiency and solutioh speed previously unavailable. Far more superior to previous MIP computer programming packages, the MPSX-MIP system, when properly harnessed, made an MIP formulation of the machinery selection problem a viable alternative.

Purpose of the Study

The primary purpose of this study is to develop a conceptual decision-making model, harness the new IBM-MPSX-MIP solution procedure and program a convenient computerized system for determining optimum farm machinery complements, where "optimum" is defined in terms of minimizing the average annual discounted cost of machinery services, given a farm mix of desired machinery practices, subject to appropriate timeliness considerations, restrictions, and other constraints as defined by their user (farmer), and whose answer will be within the realm of practical application (i.e., a farmer-available inventory of new and used alternatives).

More specific attributes desired in the system are as follows:[14]

1. The decision model should involve a full specification of the problem within the appropriate decision space of the user. The model should also provide the generality and flexibility to easily incorporate unique and varied restrictions or other considerations which might be added to the "standard" or basic machinery selection problem.

2. The decision procedure should require only information normally available or that could be available to the farmer. Data input should be easy, simple to formulate, and require a minimum of professional or programming supervision.

3. The system should be compatible to the machinery data banks, inputs techniques, and parametric definitions of the Oklahoma State University Farm Management System (Kletke, Jobes, and Brant, 1975), specifically, the OSU Budget Generator, a system alread familiar to many farmers and farm management specialists, as well as the Firm Enterprise Data System (FEDS) of the U.S. Department of Agriculture (Krenz, 1975).[15]

4. The solution algorithm used should involve, as far as possible, generally available analytical skills and conceptual talents of farm management specialists and informed farmers.

5. The system should express the suggested plan in a way which is familiar to the audience.

In other words, the model should answer the right question; fit the true problem properly; be solvable from existing knowledge; require a minimum of cost and time; reduce duplication of effort already available from other projects; allow knowledgeable interpretation by those other than the model-builder; use a generally recognized and widely taught technique so as to quickly gain user trust; and finally, provide an answer that is easily understood and directly applicable.

A secondary set of objectives for the study are (1) to apply the optimum farm machinery selection system developed in the primary objective to a set of "average" southwest Oklahoma farm situations, of varying total acreage, (2) to identify their respective optimum machinery complements, (3) to estimate the potential long-run average machinery cost curves and thereby, (4) to provide insight into a major source of economies of scale in southwest Oklahoma farming.

Outline of the Following Chapters

The introductory chapter is followed by five others. Chapter II discusses the theoretical base for the study and relates the application of a mixed integer programming framework to problems of farm machinery selection. The structure and design of an optimum machinery complement selection model cast in an MIP formulation is also developed and discussed. In Chapter III, the MIP solution algorithms are discussed as well as some heuristic solution strategies are developed. The development of a complete operating system and a description of the options available are presented in Chapter IV. The analytical framework is applied to a specific set of farm situations in Chapter V and a discussion of the resulting "solutions" developed by the model is presented. The study is concluded and summarized in Chapter VI. Implications for further research and development are also noted.

FOOTNOTES

[1]Farm size in terms of sales per unit has increased even more dramatically during the same time period. Total cash receipts and other farm income has risen from $5,093 per farm in 1950 to $32,351 per farm in 1973. Part of this increase could however be attributed to general inflation.

[2]According to the index of prices paid by farmers (1910-14=100), the cost of labor has risen significantly more than machinery prices over time (an index number (June 15, 1976) of 1769 for wages versus 1114 for tractors and 1038 for other machinery prices). Therefore, the dollar value (a nominal definition) to hour (a physical, "real" definition) ratio would tend to exaggerate the shift to machinery in the real, physical terms of technical substitution, given neutral productivity increases in both inputs.

[3]The phrase "technological treadmill" was coined in 1958 by Willard Cochrane (Farm Prices: Myth and Reality) to describe the agricultural phenomena of new technology, increased output, depressed prices and new technology.

[4]Farm wage rates (per hour and without room and board) in Oklahoma averaged $1.87 in 1973 and $2.10 in 1974 (Oklahoma Agriculture: 1974, p. 95).

[5]Sales of four-wheel-drive tractors in 1974 totaled nearly 8,300 units, compared with 6,500 units in 1973 and 3,900 in 1972. In 1975, sales are forecast to be in excess of 11,000 units, although sales of all farm wheel tractors are likely to decline.

[6]The most dramatic increases occurred in calendar 1974, when wholesale prices and prices paid by farmers for farm machinery each increased 24 percent. This rate of increase has subsided and machinery prices are inflating at a roughly similar rate to other nonfarm price indices.

[7]It is quite disturbing to find how few and outdated primary-data machinery cost studies (from which cost parameters have been or can be estimated) there are. There is, for instance, no empirical justification for using two-wheel tractor cost functions for four-wheel-drive tractors except the lack of anything better.

[8]Though this idea will be further explained and expanded in later chapters, briefly, two important dimensions of the farmer's decision space is: (1) what machinery alternatives are available to be purchased (both new and used) and (2) what machines in the current complement can be kept and incorporated into the new "optimum" complement.

[9]These attributes will be more specifically defined and enlarged upon in later chapters as the development of the model is discussed.

[10]The Farm Enterprise Data System (FEDS) uses a modified version of the Oklahoma State Budget Generator. Its primary attribute is its large geographic coverage of major crop production inputs including machinery information which is constantly being updated, projected, and maintained. (OSU Research Repot P-790, 1979.)

[11]In determining a one-tractor "optimum", the pre-determined machinery operations must be accomplished by their corresponding implements which in turn must be "pulled" with the one shared tractor. Therefore, the "buy-don't buy" decision is provided by the given operational requirements rather than by internal economic analysis.

[12]Several machinery studies by Heady and Associates (Heady and Krenz, 1962: Ihren and Heady, 9164; Chan, Heady and Sonka, 1976; and Fulton, 1976) are representative of this kind of approach. It is also important to note that the "optimum" complement must be one of the complements offered a priori in determing the envelope cost curve.

[13]The fallacy of always using "full sized" equipment has already been discussed. The Armstorn-Faris observation is, in general, only true when comparing variable (not total) machinery costs per acre.

[14]Notable among those not formerly mentioned is the work by Peart, et al. (1963) in applying mathematical programming techniques to solve so-called unit-flow material-handling systems with respect to farm machinery selection problems. Successful application depended however on the availability of integer solution techniques to handle the nulti-ordered use and nultiple-use mancines so commonplace in conventional farm machinery management.

[15]This is especially serious since most commercial farms are multiple tractor operations. The Oklahoma sample (137 farms averaging 654 acres of cropland) of ERS's 1974 Cost of Production Survey showed an average of 2.18 tractors per farm (Michaels and Krenz, 1976).

CHAPTER II

DEVELOPMENT OF A DECISION MODEL

The purpose of this chapter is to introduce and develop a quantitative decision model for determining optimum farm machinery complements. The model will be developed by first, discussing its conceptual foundations in economic theory; and second, outlining its basic assumptions, conceptual structure, and component variables.

The Decision-Making Process

A decision is a choice of one from among several alternatives available to the decision-maker. To make a choice from among alternative courses of action, the expected results of the actions--the consequences of the decision--must be considered in light of the overall objectives of the decision-maker. In general each possible action in a decision problem has different consequences. This implies that there must be some sort of "testing" of each alternative, some type of "prediction" of the consequences accruing to the decision-maker. That is, there must be some mechanism for associating with each action a consequence. We shall call such a mechanism a "model."

A model should be defined such that, when decisions are made by individuals or groups using it, the reasoning leading to those decisions--the decision-making process--will have certain desirable properties. The decisions made using the model should be communicable, repeatable, comparable, and revisable (Manheim, 1962).

Modeling for Decision-Making

To the lay observer, economists may seem overly occupied, if not fixated, with the word "model." Where it once was trite to "have a theory" on a particular subject, people now have "a model." New models are constantly being produced, though the newness of some are more closely akin to the commercial soap version of "new and improved." Much of the economics profession is certainly occupied in various stages of conceptualizing, building, modifying, updating, solving, and analyzing economic models of various types, sizes, and persuasions. As reverently as some researchers embrace their "models," one might be led to believe that, in fact, Kenneth Boulding was wrong, and modelers can make their mathematical formulations say "I love you."

Models do, however, enable us to comprehend and explain the nature of the world about us. Even an incomplete or poor model stimulates our comprehension of the universe. Models serve to structure our experience, and the business of science is the construction of models. Even an incomplete or poor model stimulates our comprehension of the functioning of the real universe.

Mathematics provides a rich language with which to depict causal and functional relationships between variables in a specified hypothesized form. A mathematical model encourages the concise and complete statement of the problem and the variables and it promotes objective decision-making. Subjective decisions will continue to be made in the original design of alternative systems, but a model capable of handling many variables allows many more factors to be quantified.

A mathematical model that is efficiently programmed for solution on a computer saves computation time (and expense) and allows larger problems to be studied. A mathematical model may also, with relative ease, permit analysis of the sensitivity of a model's solutions to changes in the parameters of the problem. Such an analysis is, in many cases, as valuable as the primary solution itself.

However, mathematics only adds the powers of precision and clarity (once one understands the language) and not any greater powers to explain economic behavior. It is certainly possible, and with great mathematical rigor, to deduce unrealistic consequences. Because mathematics and model building has become so reverred a discipline in recent years, it tends to lull the unsuspecting into believing that he who thinks elaborately or has large models and big computer bills thinks well and produces better results. This is, of course, not always the case.

Use of Theory in Model Building

Perhaps unique among the social sciences, economics shares a fairly common body of theory. While not all parts of this theory are accepted as equally useful or relevant by all economists, almost all of them explicitly or implicitly build their approach to research and the solving of various economic questions on its main propositions.

Theory is a complex intermixture of two elements. In part, it is a "language" designed to promote systematic and organized methods of reasoning. Also, in part, it is a body of substantive hypotheses designed to abstract essential features of an exceeding complex reality.

All economic theory is necessarily an abstraction from the real world. For one thing, the immense complexity of the real world economy makes it impossible for us to understand all the interrelationships at once; nor, for that matter, are all those interrelationships of equal importance for the understanding and resolution of a particular economic question. The sensible procedure is, therefore, to pick out what appeals to one's reason to be the primary factors and relationships relevant to the problem and to focus one's attention on these along. Of course, the question whether the right level of abstraction (simplification) is achieved for a particular problem under consideration is a constantly nagging one.[1]

Theory is therefore a mental labor-saving device in the sense that the individual researcher does not have to "start from scratch" with each investigation, but can draw upon those theories or laws which have come to be "accepted" over time in the formulation of hypotheses and empirical procedure (Heady, 1950). Few, if any, laws have emerged from empirical research in agricultural economics which were not already explained by or implied in the logic of economic theory. It is also true that economic principle as a useful tool has generally been developed beyond its current application as a strict analytical guide in applied research (Heady, 1949).[2]

Economic theory also provides a common logic whereby scientific objectivity and interpersonal validity of conclusions can be guaranteed. The laws or theorems of economics are a deductive set of propositions derived by rules of logic from basic assumptions. Certain assumptions are required in every exercise of reason. Nature does not provide simple answers or "truths," but more generally responds with a "This is so, provided that that is so." "That being so" is also generally given with some other proviso. For instance, one can't measure angles without assuming a lot about measuring sticks, straight lines, or other physical "laws." The recent scientific revolutions in physics are an example of how an entirely new body of thought can be constructed when one assumption or another becomes intolerable. "Unrealistic" assumptions made in constructing a model should not, as Friedman (1953) points out, be used as the sole criterion for its relative "goodness," but rather its performance in predicting or prescribing the desired results. For the decision-making purposes, it is important that the model be realistic (valid), but it is more important to have a model useful for prediction. The paradox is that the more realistic a certain aspect of a model becomes the greater the need to make assumptions that have not been tested. This is known as the principle of the "maximum loop"--"The more one wants to know about one thing, the more one has to assume about everything" (Churchman, 1965).

Relevant Economic Theory

Machinery services are inputs into the process of agricultural production. They, along with other inputs such as fertilizer, chemicals, land, and labor, are combined together in the firm to produce a desired output. Production economics is that facet of economic theory which deals with management's production decision problems.

Principles of Production Theory

A fundamental idea or abstraction of production theory is that of the production function. Discussion of production functions requires only two considerations of economic behavior; the remainder of the discussion is purely technical in nature. One first assumes producers have an aversion to losses. Secondly, producers define the flexibility of input services on the basis of cost incidence.

Production functions serve to relate the maximum quantities of outputs obtainable (at a point in time and with a fixed body of knowledge) with various combinations of inputs. The function then already presupposes a set of optimality calculations in which the many alternative ways the inputs may be combined with available technologies to produce a given level of output q have been examined. Thus, the production function serves as a boundary between the feasible (i.e., obtainable level of output with a given and well-managed set of inputs) and the infeasible (Heady, 1952). The implicit functional form in the most general case of m products (q) and n factors (x) is given by:

$$f(q_1, q_2, \ldots, q_m, x_1, \ldots, x_n) = 0 \tag{2.1}$$

The more commonly given explicit form (one product case) is given by:

$$q = f(x_1, \ldots, x_n) \tag{2.2}$$

Whereas, the functional form of the conventional graphic representation (Figure 2) is given by:

$$q = f(x_1 | x_2, \ldots, x_n) \text{ or } q = f(x_1) \tag{2.3}$$

Equations (2.1-2.3) all assume q, q_i, $x_i > 0$, for all i, as does the following mathematical derivation.

Inputs, whose costs associated with their use are either monetarily unavoidable or much greater in the current time frame than would be the case sometime in the future, are said to be fixed. There are few technologically fixed inputs. Economic fixity, however, can arise from

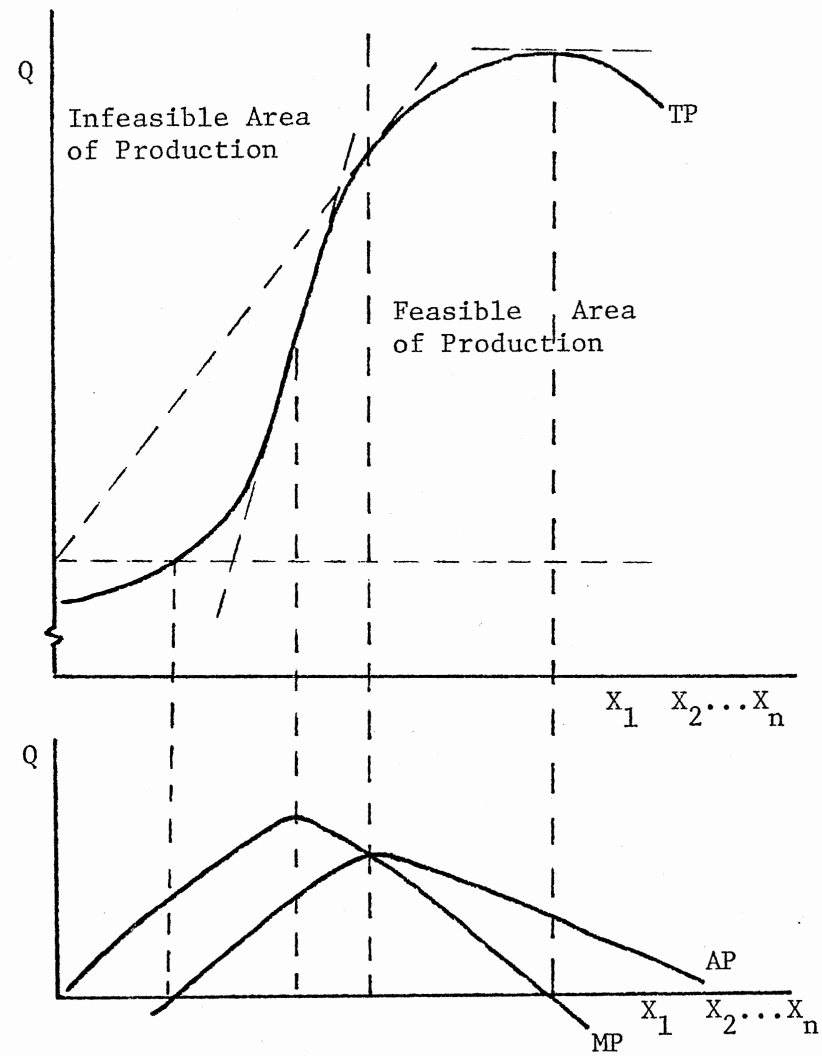

Figure 2. The Classical Production Function, Average Product, and Marginal Product Curves

contractual agreements, jointness of resource use in more than one enterprise, indivisibility of resources, and resource perishability. Inputs x_2, x_3,...x_n in equation (2.3) are represented as "fixed" inputs.

Variable inputs are those resources measured in units of application per unit of time over which the producing unit can exert cost control (i.e., the total cost of using particular input can be increased (reduced) as more (less) of the input is used).

The inputs of a production function may also be classified into several types. Given the function:

$$q = f(x_1,\ldots,x_j,\ x_{j+1},\ldots,x_{j+k},\ldots,x_{j+k+m}) \tag{2.4}$$

inputs x_1 through x_{j+k} may be classed as controllable inputs, and inputs x_{j+k+1} through x_{j+k+m} classed as uncontrollable (Heady and Dillon, 1961). The inputs over which the firm has control can then be divided into variable factors ($x_1,\ldots,x_j$) and (economically) fixed factors ($x_{j+1},\ldots,x_{j+k}$). The uncontrollable inputs are generally left out of the decision analysis, except in terms of the uncertainty and variability they might produce in the final quantity produced. Usually as the time frame of production lengthens, fixed inputs become variable. A short-run, variable-factor analysis is therefore only as "short-run" as the fixed factors define it. The "long-run" need be only as long as the time frame for which the relevant fixed factors become variable.

The marginal productivity of a particular input X_j is defined as (MP_j) the rate of change in the quantity of output resulting from incremental (small) changes in the quantity of input, x_j, holding all other input levels constant. This, of course, assumes the production function is both continuous and differentiable in the relevant region. Mathematically, this is shown as:

$$MP_j = \frac{\partial q}{\partial x_j} = \frac{\partial f(x_1, x_2, \ldots, x_n)}{\partial x_j} = f_j \qquad (2.5)$$

When all inputs are allowed to vary, the resultant change in output is given by the total differential of output.

$$dq = MP_1 dx_1 + MP_2 dx_2 + \ldots + MP_n dx_n \qquad (2.6)$$

Since dq = 0 along a given isoquant (by definition), then

$$-\frac{dx_2}{dx_1} = -\text{ slope of the isoquant } = \frac{MP_1}{MP_2} = \text{rate of technical substitution}_{1,2} \qquad (2.7)$$

Tangency between an isoquant and an iso-cost line (point A, Figure 3) means that the slope of the isoquant equals the ratio of the relative factor prices.

$$-\text{slope} = -\frac{dx_2}{dx_1} = \frac{MP_1}{MP_2} = \frac{w_1}{w_2} \qquad (2.8)$$

Rearranging equation (2.8), one can derive the following equation:

$$\frac{MP_1}{w_1} = \frac{MP_2}{w_2} = \ldots = \frac{1}{\text{Marginal cost of an additional unit of q}} \qquad (2.9)$$

Equation (2.8) is the first-order condition for minimizing the cost of producing any output and equation (2.9) states that the additional product of the last dollar spent on a factor is the same for all inputs.[3]

The isoquant must also be convex (the second-order condition):

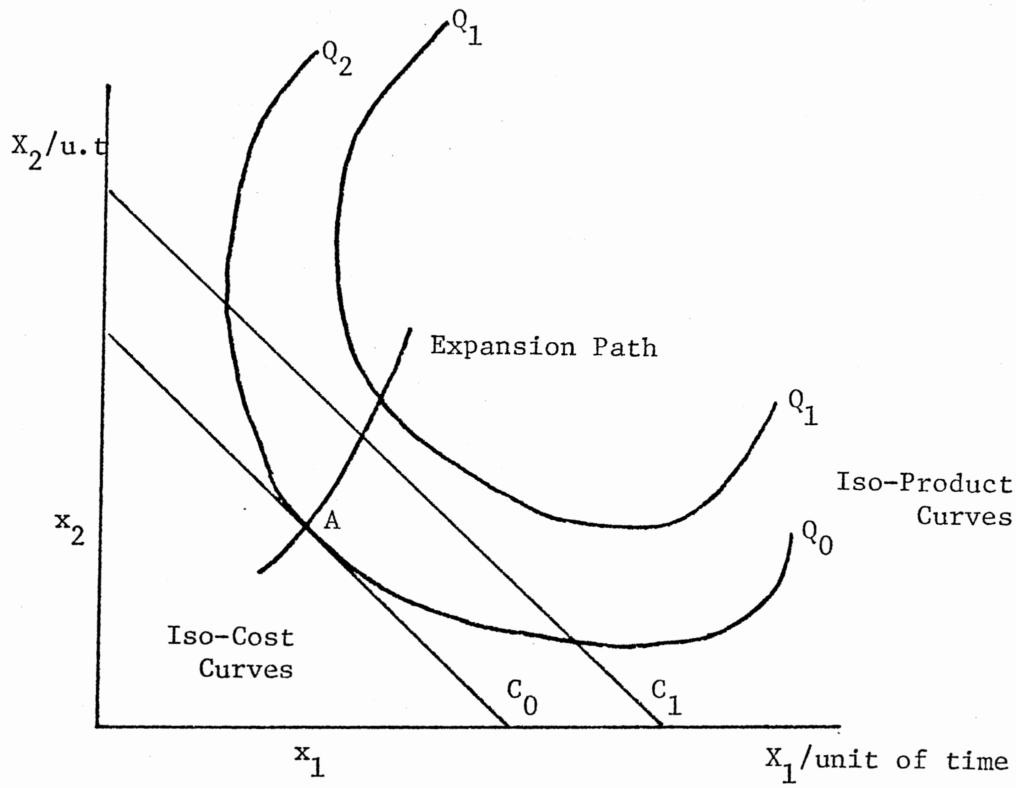

Figure 3. Iso-Product Model in Factor-Factor Space

$$\frac{d\left(\frac{f_i}{f_j}\right)}{dx_j} < 0 \quad i \neq j \tag{2.10}$$

or, equivalently, the Hessian determinant must be negative semidefinite. These conditions insure diminishing returns in the aggregate.

The Cost Side of Production

From the cost side of production, one finds the firm's total cost of production is the sum of expenditures on each variable resource, $w_i x_i$ $(i = 1,\ldots,n)$ and any accumulated fixed cost, b.

$$C = w_1 x_1 + \cdots + w_n x_n + b \tag{2.11}$$

Equation (2.11) then provides the information to draw iso-cost lines in factor-factor space as shown in Figure 3. The total differential for cost is given by:

$$dC = \frac{\partial C}{\partial x_1} = dx_1 + \frac{\partial C}{\partial x_2} dx_2 + \cdots + \frac{\partial C}{\partial x_n} dx_n \tag{2.12}$$

rearranging, for $dC = 0$:

$$\frac{dx_i}{dx_j} = -\frac{\partial C/\partial x_j}{\partial C/\partial x_i} = -\frac{MFC_j}{MFC_i}, \text{ for all } i, j, (i \neq j). \tag{2.13}$$

Minimizing the cost of production for a given level of production, $\bar{q}$, is given in mathematical terms by:

$$\min C = \sum_i^n w_i x_i + b \tag{2.14}$$

subject to:

$$f(x_1,\ldots,x_n) = \bar{q} \tag{2.15}$$

A constrained minimization such as this can be solved with the Lagrangian multiplier technique, where the augmented objective function is:

$$G = C - \lambda[f(x_1,\ldots,x_n) - \bar{q}].$$

It is necessary for a proper relative minimum that:

$$\frac{\partial G}{\partial x_i} = \frac{\partial C}{\partial x_i} - \lambda \frac{\partial f}{\partial x_i} = 0, \quad \text{for all i.} \tag{2.16}$$

These may be re-written as:

$$\frac{MP_1}{MFC_1} = \frac{MP_2}{MFC_2} = \cdots = \frac{MP_n}{MFC_n} \tag{2.17}$$

Clearly, equation (2.17) is the same condition as equation (2.9) since the marginal factor cost of input i (MFC_i) is equal to its price (w_i). Figure 4 shows graphically how closely cost and production are tied together.

Objectives of Optimum Farm Decision-Making

Economics, as a science of choice between alternatives, is based on maximizing and minimizing conditions with respect to a definable objective function. Generally, consumers are "assumed" to spend their income in a manner that maximizes their utility or well-being. Producers are assumed to use resources and organize production such that their profits are maximized. In order to "explain" the behavior of individual economic

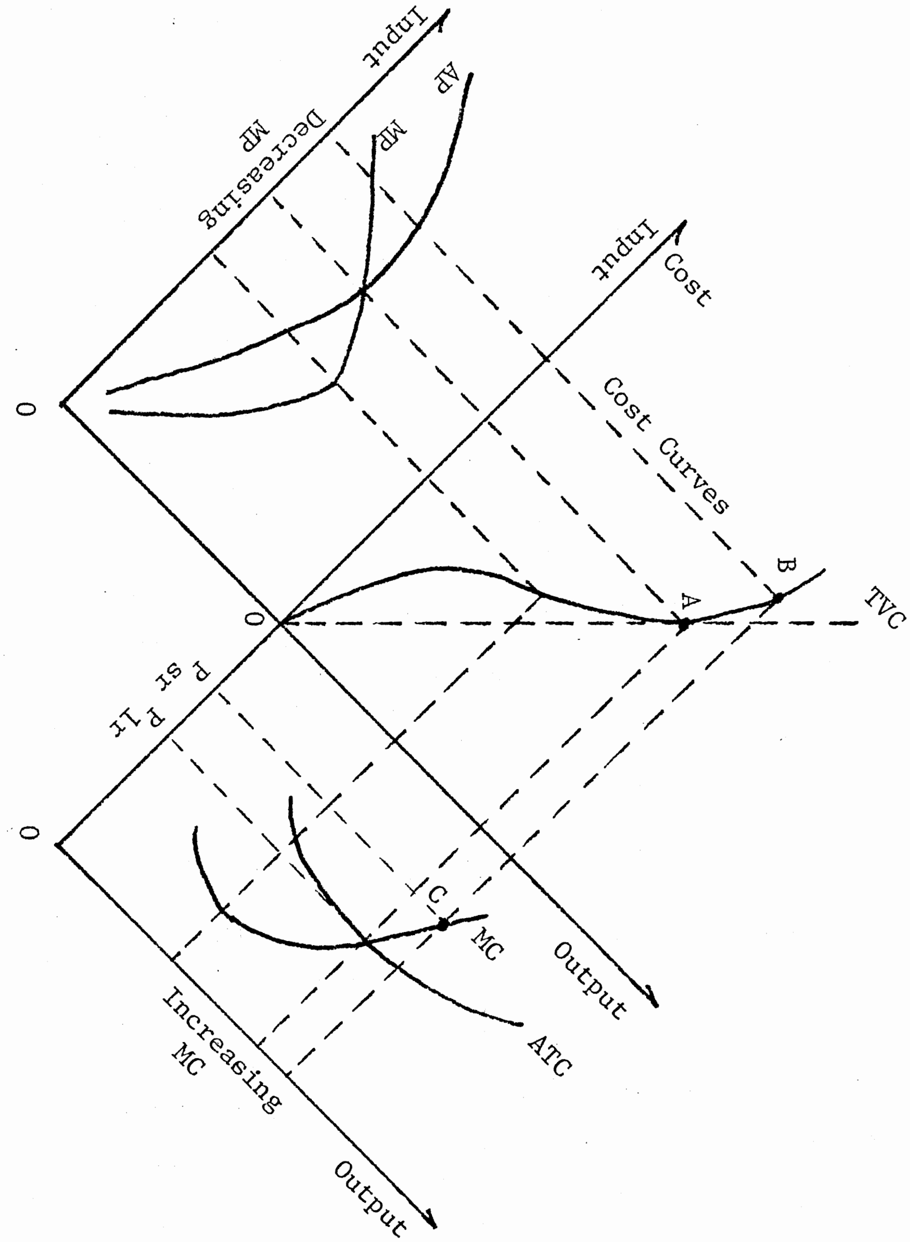

Figure 4. Graphical Relationship Between Production and Cost

units or set forth the logic of their optimum use and consumption is necessary. The farm firm (a producing and decision-making unit) and the farm householf (a consuming and decision-making unit) are closely knit not only physically but also with respect to the supply of resources and the decision-making process.

The assumption of a strictly profit-maximizing objective function for use in prescribing "optimum" resource use may rigorously provide a "right" answer, consistent with the profit-max assumption, but a less than adequate answer in promoting the overall farmer's welfare. It is obvious, for example, that a farmer might make a greater profit (for a short time if capital is available) were he to work 18 hours per day rather than 12 hours per day. However, at some point the direct utility from rest and leisure becomes greater than that derived from goods bought with greater farm profits. Perhaps hitting closer to home is the input of additional capital (air-conditioned cabs, steros, etc.) or consumables to make working conditions more pleasant or the labor less strenuous.[4] The commonly made statement that something is "not worth the trouble" many times implies the consideration of factors beyond equating marginal revenue to marginal cost.

There are a number of proposed substitutes or additions to the economists' favorite profit-max objective function. There are, of course, personal motives of various types which can be maximized. Insuring the long-run survival of the firm or the maximization of sales or growth in net worth are a few. Profit, personal motives, firm survival, growth, and others may also be combined into some overall "utility" function which could then be maximized as a single objective function.

Alternatively, it could be said that a farmer's goal has many dimensions and each one is an aspiration level. Each aspiration must then be satisfied (this would constitute a restriction on the maximization of the other "dimensions") or maximized. Certainly to be realistic, it is necessary to assume that a number of goals exist. To exclude all but one from the decision framework, while it would simplify the world of the analyst, provides little for the decision-maker beyond satisfying some academic curiosity.

The mathematical analysis of the last section also assumed that the entrepreneuer is faced with, or has at his disposal, perfect knowledge and unlimited capital. Therefore, it is sufficient to suppose that the profit-maximizing decision-maker always chooses to extend output along a factor-product curve (say, point A to point B in Figure 4) to the point at which marginal cost equals marginal revenue (i.e., point C, Figure 4). But recent literature acknowledges, and is as much devoted to, production under uncertainty, where capital is limited, and output is not extended to maximize profit (to the point defined under certainty) (Heady and Olson, 1953). Because of risk aversion and external capital rationing or both, few farmers consciously extend their output to a level (under conditions of certainty) where marginal cost equals marginal revenue. Perhaps it is more nearly true that a farmer has a "job to be accomplished" based on past experience and is primarily concerned with the least-cost method of doing it (Heady and Olson, 1953). He then enlarges the job until it's not "worth the trouble." This more practical concern of most managing farmers is also ultimately consistent with a profit-maximizing or utility-maximizing framework, since the most "profitable" output (and therefore, mix of inputs) is defined along the cost-minimizing expansion path. Unless output follows the expansion path of least-cost, the most profitable (or position of greatest utility) level will not be attained. Neglect of this least-cost consideration may also cause other goals to be unattainable.

One might then see the cost-minimizing approach to the farm machinery selection problem as an acceptable framework in which to cast a machinery management decision aid for the farmer. A cost-minimizing model can be readily extended into a profit or utility maximizing mold or subjected to any number of utility (preference) constraints. A cost-minimizing model therefore exhibits a flexibility for helping to answer a wide variety of machinery management problems under various formulations of the firm's (or farmer's) objective or preference function.

Machinery Selection Via the Production Function

A basic assumption of conventional economic theory of production is that the production function is known. In actuality, whether the function is known or not is a matter of some ambiguity and uncertainty. Certainly rare is the industrial or agricultural firm that explicitly "knows" and charts its own production function from zero input use to infinity. But, without a thorough analysis of the choices open to the productive unit (in terms of alternative ways of combining various inputs at various intensities of use and the productivity of each method), the economists' prescriptions for profit-maximization are nonoperational. Economists have in the past looked upon the production function as a boundary of its domain of competence and relegated its quantification or lack of quantification to the production engineers and physical scientists. The result, of course, is the noticeable lack of knowledge in the nature of most agricultural production functions especially in forms usable for economic decision-making.

The production of farm commodities involves numerous relationships between resources and commodities. Products such as wheat, corn, milk, or cotton are forthcoming only as a large number of input factors (both controlled and uncontrolled) are combined together. The production of wheat, for example, involves the transformation of carbon dioxide from the atmosphere, moisture and nitrogen from the soil, energy from sunlight, along with services of labor, machinery, and management, into the final saleable commodity.

Agricultural production is also primarily a biological process which not only "takes" time (in classical economic production theory, production is instantaneous within the time reference), but the timing of the application of various inputs is very important (Georglcu-Roegen, 1972). This temporal management of inputs creates a complex definitional problem of identifying the various "inputs" of an agricultural production function. For instance, the production input of plowing a field may need be quantified in terms of when the plowing takes place in reference to the other controllable (e.g., other tillage operations) and uncontrollable (e.g., weather, moisture, and groud temperature) inputs, or perhaps by how the plowing is accomplished (e.g., how deep or shallow), or whether the "input" has been applied previously in the same production cycle, or all of the above. Here "plowing" is discussed more in terms of the operational change made to the soil rather than the particular instrument used and the process of dragging it across the field.

The same definitional problem arises, for instance, in the case of fertilizer. The input may be defined as the available nitrogen in the soil at a particular point in time or as the application of anhydrous ammonia (or some other combine). What can be attributed to the marginal product of the input depends very much on the definition of the input. In one sense, there are inputs to the production function and various ways, means and times to supply the inputs during the transformation process. In an alternative sense, the ways and means and timeliness are classified as inputs as well.

It is therefore possible to define just about as many different "inputs" in the specific quantification of a production function as there are conceivable methods of utilizing and combining the more commonly delineated input list. Land, labor, and capital are three well-known "input" catch-alls for all input involved in the transformation process. While this type of simplification is okay for general theoretical exposition, it is not very helpful in formulating a management plan in the "real" world.

Another problem is that many agricultural inputs are only available in discrete units. For instance, one-half a tractor cannot be purchased, though one whole tractor of a smaller size might be. The smaller tractor however is not necessarily a good substitute for what might be, in a completely divisible world, one-half of a large tractor. In a similar vein, most machinery services can be classed as discrete operations. For instance, one either plows a field or he doesn't. Half-plowing a field makes no real operational sense. Machinery services are also not likely to be additive, at least during a given time frame. Given two consecutive plowings of a field, the second application of the plow might be in a sense providing a different "service input" than the first. Also, obvious is the need for the production function to be defined at a zero level of input of one kind or another. The possibility of such a "corner" solution among inputs is highly probable.

Continuous and differentiable production functions are generally assumed in theory. In practice, however, there are many mathematical "corners" and "gaps" which must be overcome in optimizing agricultural production functions.

Clearly, the use of agricultural production functions (even if they could be had) to determine optimum farm machinery complements and optimally scheduled machine use as prescribed by economic production theory, is precluded by the severe mathematical complications involved in the obvious functional discontinuity on the input application side as well as the product side. However, as previously discussed, the production function is only one face of a two-sided coin. On the other side are analogously determined cost functions.

Machinery Selection Via the Cost Function

In order to isolate the cost side of production, as it involves machinery selection and use, one must still provide a production function which will help identify the relevant cost components.

Assume the following production for crops:

q = F (seed, fertilizer, cultivation practices,...,land)

Cultivation practices include pre-plant as well as post-plant operations. The practices may be completed by various combinations of power and equipment as well as types of equipment. The production function may be written as:

$$q = F(X_1, X_2, \ldots, X_c, X_{c+1}, \ldots, X_{c+d}, \ldots, X_n); \qquad (2.18)$$

$c+d < n$

$0 < d$

where X_1 are variable resources. The variables X_c through X_{c+d} are cultivation practices required to complete the production process. The cultivation practices can be performed by various power and implement combinations, at various levels of intensive use, and degree of timeliness in which operations are carried out. That is, X_i $(i = c,\ldots,c+d)$ is a function (Y_i) of alternative combinations of tractors and implements (M), utilization rate of M(O), and degree of timeliness (T).

$$X_i = Y_i(M,O,T); \quad i = c,\ldots,c+d \tag{2.19}$$

In most agricultural production function presentations, the machinery inventory, M, the operational use of the machine complement, O, and the timeliness factor, T, are generally considered, fixed at a certain level along with other fixed inputs. However, in this analysis, let the normally variable inputs become fixed at some predetermined level of input and maintain for analysis the factor inputs M, O, and T.[5]

Investment or durable inputs, such as tractors, implements, as well as barns and fences, have always been troublesome in production analysis since they combine both stock and flow concepts. Smith (1961) dismisses the capital flow approach by converting stock assets into flow inputs on current account (effectively eliminating the problem by definition), and substitutes in his analysis a formulation where output varies with the physical quantities of durable assets present in the production process. Durable resources are assumed to add value (at a constant rate) to the production process, in a sense, by their very presence. While this formulation provides for substitutability between durable factors and variable inputs, it does not allow for the substitutability of a more intensive use of a capital good for marginal increases in its stock.

In equation (2.19), substitution between the stock of machinery assets and the intensity of the machinery use is explicitly defined by separating into two variables (M and O), the stock and flow characteristics. Consistent with economic theory, one could expect that as the cost of machinery investment, M, increases relative to the cost of the other variables, the use of input M would not increase and perhaps decline. By the same token, if the cost of operating machinery increases due, for example, to an increase in the cost of labor, one could expect a decline in the employment of input O and perhaps an increase in input M. This example represents classical capital-labor substitution in the production input mix (Idachaba, 1972).

Separating the stock and flow characteristics into two variables also allows separation of the cost components. Namely, the ownership or fixed costs associated with machinery would be appropriately attached to M and operating or variable costs would be attached to levels of O. If the two concepts are combined, then so must be the associated costs. Since the ownership costs are fixed with respect to use, the true marginal cost function is discontinuous at zero and higher discrete capacities of use (Figure 5). If the operating cost above zero use (up to capacity) is assumed linear, one frequently (mis)-used approximation that is continuous is shown by TC_3. However, the marginal cost (and total cost at any other level of use than X and 2X) of an additional unit of machinery services of this function is much higher than the true marginal cost (MC_3 versus MC_1).

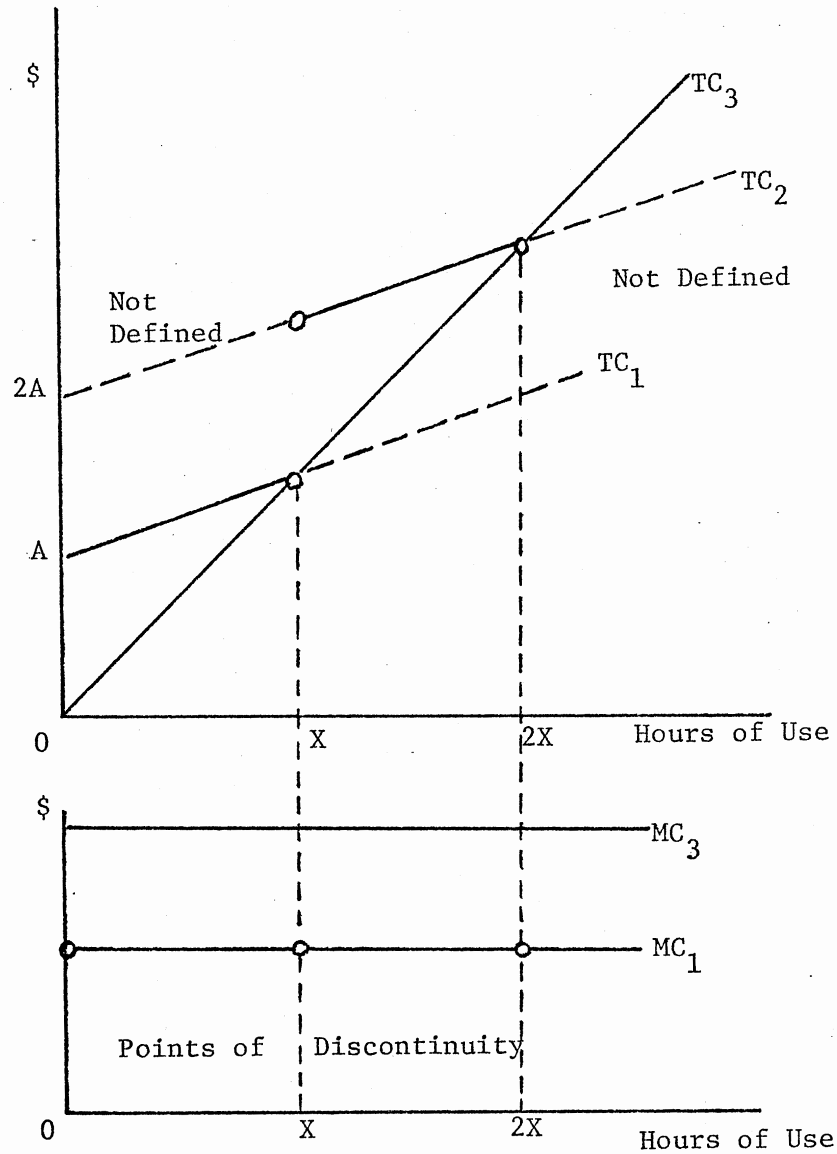

Figure 5. Machinery Total and Marginal Cost Functions Displaying Discontinuous Points

Ownership Costs

The cost associated with a given level of factor M is what is normally designated as those attributed to the ownership of machinery. This ownership cost includes charges for depreciation, interest on investment, taxes, insurance, and shelter.

Depreciation. Depreciation is typically the largest cost-of-ownership item and is the cost associated with the loss of value resulting from normal wear and obsolescence. Machines depreciate, or have loss of value for several reasons, including:

1. Age - Even though model changes may have resulted in little difference in the function of a machine, the newer machine is worth more than an old one.

2. Wear - The more a machine is used, the greater the wear on non-replaceable parts. As a result, the ability to function like new may be reduced or it may keep breaking down (lose its reliability).

3. Obsolescence - If there has been a major model change or a machine no longer has enough capacity, its value may be greatly reduced--even though it may not be worn out. New machine concepts may also be introduced which may obsolete existing similar machines.

There are several different ways to calculate depreciation, including those methods used for figuring income tax. Three methods commonly used to compute depreciation are:

(1) Straight-line depreciation

(2) Sum-of-the-digits depreciation

(3) Declining-balance depreciation

The computation aspects of these methods are discussed elsewhere (Williams, 1977). Bowers (1970) proposes, for example, a modified double declining balance method to estimate the remaining farm value. The remaining value (RV) formula is given as:

$$RV = RFV1 \times XLP \times RFV2^{YRS} \tag{2.20}$$

where XLP is the initial list price,

YRS is the number of years the operator expects to own the machine,

RFV1 is the first-year correction factor (for tractors, RFV1 = 0.68), and

RFV2 is the parameter of the standard declining balance equation (e.g., for tractors RFV2 = 0.92).

The declining-balance depreciation method better reflects the actual value of a machine at any age than either the straight-line method or the sum-of-the-digits method. With the declining-balance method, a machine depreciates a different amount for each year, but the annual percentage of depreciation is the same. In actual practice, the first-year depreciation is considerably higher, percentage-wise, than later years. To provide a more accurate method for estimating the value of machines, Bowers (1975) adds a first-year correction factor to the declining-balance formula.

However, the approach to investment decisions in the context of a factor M in equation (2.19) requires a constant average annual estimate of depreciation over the service life of the particular machine. For this, the straight-line method is more appropriate.

The straight-line method of calculating depreciation is quite popular due to its computation ease and because it provides a good approximation for many assets. With this method, the amount of depreciation is assumed to be the same each year during the expected life of the asset. The formula for computing the average annual depreciation (AAD) by the straight-line method is:

$$\text{AAD} = \frac{\text{Cost - Salvage Value}}{\text{Years of Expected Ownership}} \tag{2.21}$$

The straight-line depreciation method is not quite accurate for giving the true value of a machine at some age short of the end of its assumed life. In actual practice, machines depreciate much faster in the first few years than in later years. The straight-line depreciation method is better for estimating costs over the entire life of the machine. As long as the salvage value of a machine is its actual value at the end of its life, average annual depreciation costs can be estimated accurately with this method.[6]

Interest. The interest charge included in annual overhead cost is typically the second largest cost-of-ownership expense. Interest on the investment in a farm machine, whether or not the money invested was borrowed, is always a cost since the money may be used for other productive purposes. Also, the interest rate should be based on the opportunity rate of return rather than actual interest costs. Voluntary or involuntary capital rationing may cause the appropriate rate to be significantly higher than the "market" rate of interest.

The interest cost component of the annual ownership charges is generally calculated on the average value of the asset. The usual method of determining the average value for an asset is:

$$\text{Average Value} = \frac{\text{Initial Cost + Salvage Value}}{2} \tag{2.22}$$

with the result multiplied by the opportunity rate of return to determine the annual ownership charge for interest. Since we are concerned with a depreciable asset, this formula is justified on the basis that it represents the "average" remaining value over the asset's useful life.

However, this procedure consistently understates the true ownership interest cost (assuming depreciation accrues as calculated by the straight-line method).

To accurately account for the opportunity cost of the investment, the annual charge (in equal installments) for depreciation and interest must be an amount which, when invested at the opportunity rate of return for the remaining life of the asset and added to the salvage value recovered at the end of useful life, will just equal the amount which could have been obtained by investing in the alternative investment (Kay, 1974). The formula which will accomplish this objective is:

$$\text{Annual Charge} = \frac{C(1+r)^n - SV}{[(1+r)^n - 1]/r} \tag{2.23}$$

where C is the initial cost of the asset;

SV is the salvage value;

n is the useful life in years; and,

r is the opportunity rate of return in dollars per dollar invested.[7]

The numerator in equation (2.23) is the future value of the alternative investment at compound interest for the life of the asset less the salvage value. The denominator is the factor for determining the future value of an annual annunity received at the end of each year for n years.

Taxes. Taxes are paid on machinery in the same manner as for other property. Tax costs vary from one place to another but are generally a function of average value. The annual charge for taxes would be from one to two percent of the value of the machine. In some cases, a sales tax is also assessed when the machine is purchased.

Insurance. Insurance policies are usually carried on more expensive machines while the risk of loss is usually assumed by the farmer on the simpler, less expensive machines. Whether the farmer or an insurance company carries the risk, a charge (premium) for possible loss should be made. In most cases, an annual charge for insurance or risk represents about 0.25 to 0.50 percent of the remaining value of the machine.

Shelter. There is a tremendous variation in farmers' use of shelter for agricultural machinery storage. If housing is not provided, machines will deteriorate faster and, in general, higher ownership costs will result due to unprotected storage. Typical annual costs for providing shelter will average one to two percent of the remaining value of the machine. This charge should be made whether shelter is provided or not.

Operating Costs

The costs associated with operating the machinery complement in performing cultivation practices, factor O in equation (2.19), include charges for fuel, lubrication, repairs and labor.

Fuel Costs. The most accurate method for estimating fuel costs are accurate records on similar machines and operations. However, in cases where actual records are not available, estimating the fuel costs is possible because the amount of fuel consumed is directly related to the amount of energy exerted.

The amount of energy needed per acre for performing operations, such as disking or plowing, is nearly constant, regardless of speed and size of the tools and tractor being used. The amount of fuel needed per acre is in proportion to the amount of energy required. One measure of the amount of energy used is in units of horsepower-hours.[8] The amounts of energy required for typical farm operations, in horsepower-hours per acre, are shown in Table 4.

For the same amount of work, diesel engines will average about 70 percent as many gallons as gasoline engines. LP-Gas engines require about 20 percent more fuel than gasoline engines. Diesel engines have become almost standard in tractors over 100 horsepower due to their fuel efficiency. For year-round operations of main power units, a gallon of gasoline averages 9.0 PTO horsepower-hours, a gallon of diesel averages 13.0 PTO horsepower-hours, and a gallon of LP-Gas averages 7.5 PTO horsepower-hours (Bowers, 1975). However, engines of a given horsepower rating do not transmit power at all levels of load with equal fuel efficiency (Table 5). In fact, fuel efficiency can drop rapidly as the load as a percent of maximum rated horsepower declines. Diesel engines, however, have excellent part load fuel economy (Bowers and Paine, undated). Naturally, some tractors are more efficient than others. Data from the Nebraska Tractor Test can be used to adjust these average figures to ones more specific to the size and make of a particular tractor alternative.

Tractor fuel consumption per hour (TFC) can be estimated on the average with the following formula:

$$TFC = FE \times PTOHP \tag{2.24}$$

where FE is the fuel efficiency in gallons of fuel per horsepower-hour.

For gasoline engines, $FE = .54L + .62 - .04 \sqrt{697L}$

Table 4. Average Energy and Fuel Requirements of Selected Operations

Operation	Energy Required, PTO HP-Hrs. Per Acre	Gallons per Acre Gasoline	Diesel	LP-Gas
Shred stalks	10.5	1.00	0.72	1.20
Plow 8-inches deep	24.4	2.35	1.68	2.82
Heavy offset disk	13.8	1.33	0.95	1.60
Chisel plow	16.0	1.54	1.10	1.85
Tandem disk, stalks	6.0	0.63	0.45	0.76
Tandem disk, chiseled	7.2	0.77	0.55	0.92
Tandem disk, plowed	9.4	0.91	0.65	1.09
Field cultivate	8.0	0.84	0.60	1.01
Spring-tooth harrow	5.2	0.56	0.40	0.67
Spike-tooth harrow	3.4	0.42	0.30	0.50
Rod weeder	4.0	0.42	0.30	0.50
Sweep plow	8.7	0.84	0.60	1.01
Cultivate row crops	6.0	0.63	0.45	0.76
Rolling cultivator	3.9	0.49	0.35	0.59
Rotary hoe	2.8	0.35	0.25	0.42
Anhydrous applicator	9.4	0.91	0.65	1.09
Planting row crops	6.7	0.70	0.50	0.84
No-till planter	3.9	0.49	0.35	0.59
Till plant (with sweep)	4.5	0.56	0.40	0.67
Grain drill	4.7	0.49	0.35	0.59
Combine (small grains)	11.0	1.40	1.00	1.68
Combine, beans	12.0	1.54	1.10	1.85
Combine, corn and grain sorghum	17.6	2.24	1.60	2.69
Corn picker	12.6	1.61	1.15	1.93

Source: Bowers, 1975.

Table 5. Fuel Efficiency in PTO Horsepower-Hours per Gallon by Fuel Type and Load Level

Load Level	Fuel Efficiency		
(percent of capacity)	(PTO horsepower-hours per gallon)		
	Gasoline	Diesel	LP-Gas
100	9.57	12.87	7.88
80	8.65	12.48	7.44
60	7.22	11.04	6.52
40	5.61	8.74	5.17
20	3.65	6.04	3.65

Source: Hunt, 1977.

and for diesel, $FE = .52L + .77 - .04\sqrt{738L + 173}$

and for LP-Gas, $FE = .53L + .62 - .04\sqrt{646L}$

where L is the load level (PTO hp used/max. PTO hp) and,

PTOHP is the rated maximum PTO horsepower of the tractor.

Fuel cost per hour would equal fuel consumption per hour (TFC) times the price of the fuel in dollars per gallon (Hunt, 1977).

Lubrication Costs. Total engine lubrication costs are generally estimated at 15 percent of total fuel costs and include the cost of crankcase oil, grease, transmission and hydraulic fluids as well as appropriate disposable filters.

Repair Costs. With any machine there are four main types of repairs. These types are:

(1) Routine wear,

(2) Accidental breakage or damage,

(3) Repairs due to operator neglect,

(4) Routine overhauls.

Typical examples of routine wear (or replacement) would include plowshares, disk blades, sickles, tires, and batteries. Even with the best of care, replacement will be necessary sooner or later. Machinery accidents can happen, but good judgement can eliminate most accidental breakage. If the "time" is not taken to perform needed repairs and maintenance, they almost always lead to more serious and costly problems. Routine overhauls are needed to replace worn or defective parts and restore original performance.

Studies of machinery repair costs indicate a wide variation in costs according to the kind of machine and the way it is used. While it is difficult to estimate repair costs for a particular machine accurately, Bowers (1970) has developed a set of equations which can serve as guidelines. Bowers' equations estimate the total accumulated repairs for the number of years ($TAR) the machine is expected to be owned as a function of the current age of the machine and its list price, as follows:

$$\$TAR = \$LP \times RC1 \times RC2 \times L^{RC3} \tag{2.25}$$

where $TAR is the total accumulated repairs;

$LP is the initial list price of the machine;

RC1 is a repair cost constant computed as the ratio of total expected lifetime repairs to the initial list price;

RC2 and RC3 are repair cost constants that together determine the general shape of the accumulated repair cost curve; and,

L is the percent of machine life at the point where accumulated repairs are to be measured.

Repair cost per hour of machine use can then be computed using equation (2.26).

$$\$REP = \frac{\$TAR}{HRSUSED \times YEARS}$$

where $REP is the expected cost per hour of machine operation;

$TAR is the total accumulated repairs computed in (2.25);

HRSUSED is the estimated number of hours that the machine is used annually; and,

YEARS is the years the machine is expected to be owned.

The purpose of repairing a machine is to maintain its reliability and to keep it performing its task properly. Reliability is hard to measure with a formula as it expresses the amount of confidence placed in a machine to perform without an unplanned time loss due to a breakdown. The above repair cost functions do not account for the timeliness losses due to unplanned repairs. As a rule of thumb, it pays to spend one to two days in machinery maintenance and repair time in the "slack" season in order to avoid a one hour loss when the machine is needed (Bowers, 1975).

Labor Costs. Obviously at least one hour of labor is required to operate the tractor pulling an implement for one hour. The effective field capacity (EFF) of the implement compensates for lost time due to turning, materials handling, field adjustments, minor repairs, unclogging, and other interruptions. Additional tractor operating time (and labor time) is needed for travel to and from fields, machine setup, initial adjustment and equipment calibration. More operator time (over that just mentioned) is required for daily servicing of the tractor and breakdowns not compensated for otherwise. The total expected labor requirement for a particular machinery operation should compensate for all of the above labors.

The labor component cost involved in farm machinery may or may not be a direct cost to the farm firm. For owner-operators, labor costs may be determined from alternative opportunities for the owner's time whether they be off-farm employment or other on-farm enterprises. For hired operators, a constant hourly rate might be more appropriate, depending upon how labor is hired or available in local areas. It is important to note that leisure is also an important demander of time willing (in a sense) to pay a relatively high price for marginal increments of a laborer's time.

Total Operating Cost Per Acre. In order to convert machinery costs per operating hour to a dollar cost per acre, the number of hours the machine must be operated in order to complete one acre of "work" must be computed. Machine capacity, when measured in acres per hour, is determined by three factors: (1) speed, (2) width, and (3) efficiency. The factor to convert machinery cost per hour into machinery cost per acre is as follows:

$$\text{HPA} = \frac{8.25}{(\text{SPEED x WIDTH x EFF})} \qquad (2.27)$$

where HPA is the hours required to cover one acre;

SPEED is the effective speed (miles per hour) of the machine as it travels over the acre;

WIDTH is the number of feed covered by the implement in one pass; and,

EFF is the field efficiency of the machine or ratio of the actual capacity of the machine to its theoretical capacity.

Therefore, total operating costs per acre for a particular operation would equal the hourly expenses of the implement and the tractor, plus labor, times the number of hours required to complete one acre of work.

Timeliness Costs

Until a few years ago, only such items as break-even points, partitioning of costs, and amortization of capital expenditures were discussed in machinery management sessions. While these topics are certainly important considerations, they alone are in no means adequate to describe the productivity characteristics of machinery that regulate the uses of farm machinery.

Timeliness, factor T in equation (2.19), is the ability to perform and complete a job or task at or during the "optimum" time (in terms of achievable product quality and quantity). As previously mentioned, the application and use of inputs in the production process are dispersed intertemporally in combination with biological processes and environmental events. Clearly, the timeliness of a field operation can have economic value (for example, a "late" planting or harvesting can significantly reduce yields). Cultivation must be accomplished during specific stages of plant growth, or production suffers. Seedbed preparations must be accomplished in a timely manner to allow time for the last crop's plant debris to decompose, or to be ready to catch perennial rains or allow a maximum number of days in the growing season.

Small implement-tractor combinations with low field capacities may be very costly, if the net yield (and therefore, total revenue) is reduced because of the length of time required to complete the field operation. The inability ofan implement to complete a job within a maximum return period (untimeliness) can be considered as a charge against that implement. With these non- "out-of-pocket" charges or opportunity costs included, the "optimum" size of the implement will generally be greater than the "least-cost" size, as shown in Figure 6. The optimum machine capacity balances the low ownership cost advantage of small capacity machines with the timely-operation advantages of the large machines.

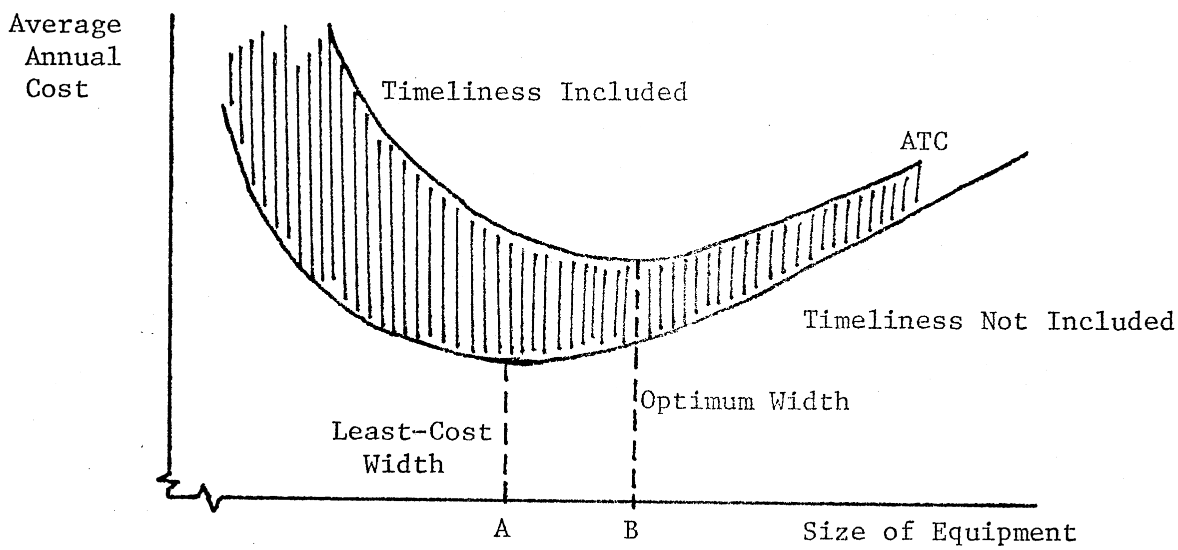

Figure 6. The Effect on the Optimum Size of Equipment When Timeliness Costs are Included in Total Costs

The amount of the (un)timeliness charge or the prospect of incurring it is determined by the shape of the timeliness cost function. Some operations may be accomplished over a period of days or weeks without incurring any timeliness penalties. For others, the penalties may only slowly accumulate and then rapidly accelerate after a certain point. For a few operations, the ideal time may be but a fleeting moment before or after which substantial losses in yields or product quality are incurred. Figure 7 portrays in the first two frames the types of function just mentioned.

In the first frame (a) of Figure 7, the ideal time period to accomplish the given task is designated at X_0 and is momentary in length. For this exercise, the distance between X_B and X_E is the length of time required to accomplish the given task with the subject machine. Since the timeliness cost of beginning before the optimum point and completing the task after X_0 are equal per marginal unit of time (i.e., the slopes of the penalty function are equal in absolute value), the task initiation and completion time points are evenly distributed from X_0 (line segment $\overline{BF}$). The timeliness costs incurred amount to the sum of line segments $\overline{BC}$ and $\overline{FE}$.

In the second frame (b) of Figure 7, the task can be (and must be) started at X_1 or after, and completed by X_2 or before. Any part of the task extending outside of these two bounds incurs an infinite timeliness cost.

In the last frame (c) of Figure 7, the interaction of two timeliness cost functions and their effect on task scheduling is graphically displayed. In this case, a V-shaped timeliness function and task (similar to frame (a)) may potentially compete for available time with a

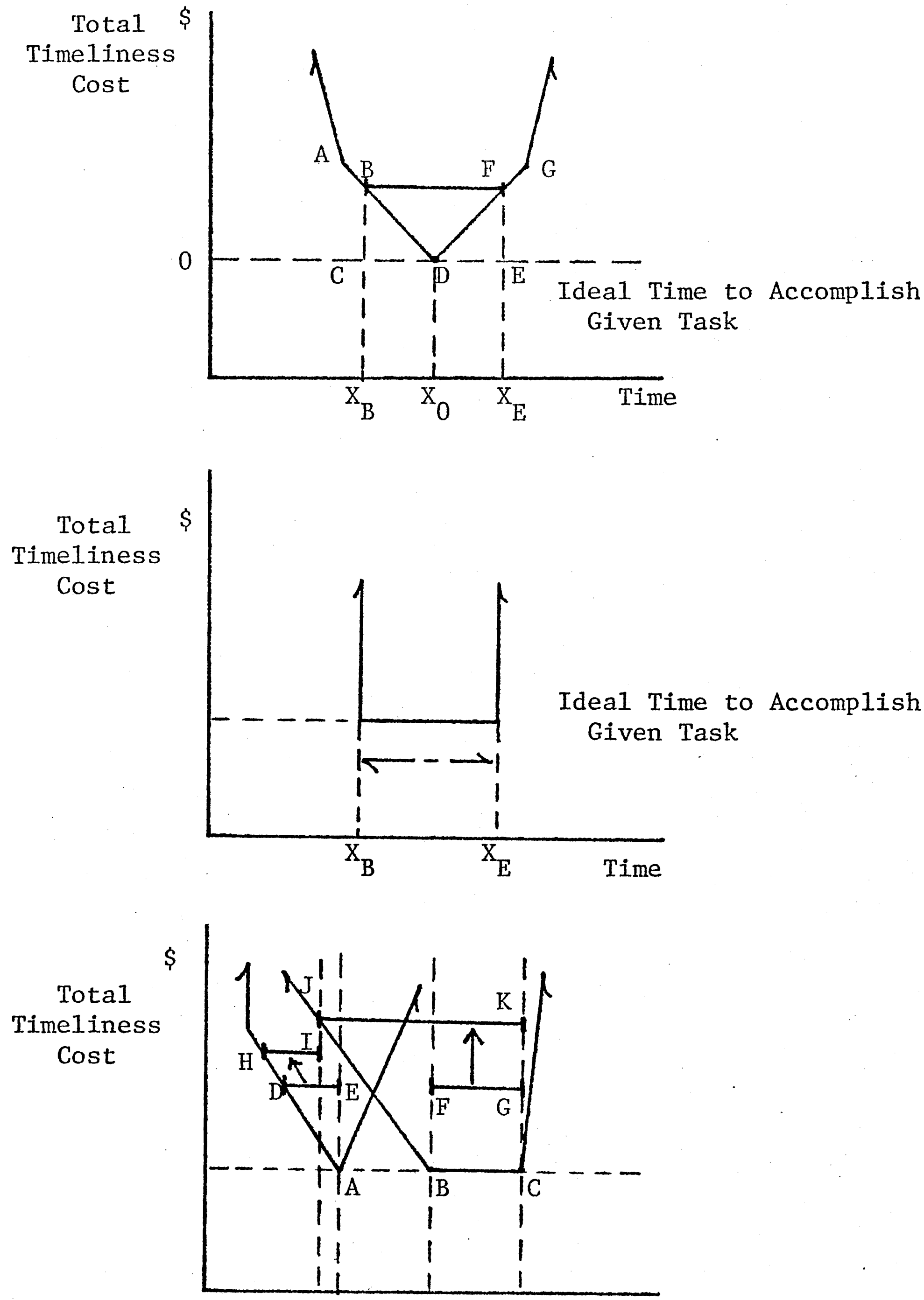

Figure 7. Timeliness Cost Functions Showing Alternative Functional Forms and Scheduling Effects of Timeliness Interaction

modified U-shaped cost function and task. The story begins with task 1 and task 2 minimizing timeliness charges by scheduling represented by line segments $\overline{DE}$ and $\overline{FG}$. Note that task two is incurring no timeliness losses and task one has begun relatively early due to the relatively low timeliness cost vis-a-vie after x_0^1. Now say, a smaller implement is now used for task two, and therefore increases the span of time required to complete the same task from $\overline{FG}$ to $\overline{JK}$. Since the marginal timeliness cost (MTC) of shifting task two's completion time to the right (later) is higher than the MTC of shifting task two to the left (earlier) plus the MTC of shifting back in time the start of task one, the scheduling changes are indicated as $\overline{HI}$ and $\overline{JK}$. Had the right-hand MTC of task two been sufficiently lower, task one would not have been displaced task two and line segment $\overline{JK}$ would have moved more to the right. Of course, as the number of tasks increase, both within a particular time period and on a continuum of time "periods," the scheduling process becomes exceedingly more complex.

A time period, for purposes of this study, is defined as a span of time during which a zero timeliness cost is defined (but not necessarily for any or all given tasks) and an estimated number of hours available for tillage operations is given. For example, frame (b) of Figure 7 would be represented by a single time period. Frame (a) and (c) might be formulated into five interrelated time periods under one global time period.

Quantitative determination of timeliness coefficients is a time-consuming task because multiple tests and measurements must be made, many of which are under conditions in which crop value may be lost just for the purpose of securing timeliness data. Consequently, the amount of data available on timeliness coefficients is very limited. In addition, each value is very much linked to the particular soil, weather, and crop conditions under which it was developed; thus, such values can only serve as estimates when applied under other circumstances (Chancellor and Cervinka, 1974).

Research is underway to develop universal crop yield models which show the response of grain yield to both weather and cultural practices (Feyerherm, 1977). Universal yield equations in which such items as planting times, cultivation times, and others are included could easily be transformed into timeliness loss equations.

Models incorporationg a soil moisture balance approach have also been used in the estimation of favorable field working days in Illinois (Elliott, Lembke, and Hunt, 1977). Similar methodologies have also been used to calculate the number of field working days in South Carolina (Kish and Privette, 1974).

Actual records of observed numbers of days suitable for field operations in Iowa were analyzed by Fulton et al. (Fulton, Ayres, and Heady, 1976) and estimates of the minimum number of suitable field days were made at four probability levels. Significantly, estimates for short periods were found not be additive for longer periods at a specific probability.

Reinschmiedt (1973) determined for Southwest Oklahoma a set of relationships between different rainfall amounts and the subsequent field time losses. Simulated daily rainfall data were incorporated with a matrix of rainfall work-loss relationships into a computer simulation model and a "days-available-for-tillage" cumulative distribution was found. From these cumulative distributions the number of days available from any percentage level of timeliness (e.g., a 90 percent timeliness level says that 90 percent of the time one may expect at least the specified number of days available for tillage) can be found. Establishing the number of hours per day an individual is willing to work and multiplying that by the number of days available and the number of available operators determines the field hours available in a time period.

Hours Available

Unfortunately, few, if any, field machinery tasks are all-weather operations. In Iowa, rain is probably the greatest, most uncertain and most prevalent time-loss factor in determining the days or hours available in time period for machinery operations. Rainfall increases the moisture content of the soil which, depending upon the soil type, greatly changes the soil texture (e.g., plowing a field when it is too wet will tend to cause hard clods to be formed when it finally dries), and greatly reduces the productivity of some tillage operations (e.g., sweeping a field to control weeds will do little good if the ground is wet). A recent rainfall may also decrease the flotation and traction properties of the soil below that necessary to support and operate tillage machinery. Alternatively, the soil can also become too dry and hard for tillage equipment to pierce and cultivate.

Northern areas of the United States may have the time available limited by snowfall or the freezing of the soil. Other weather conditions, such as lightning storms and tornadoes, also may cause the cessation of machinery operations during a scheduled time period. Therefore, depending upon the situation, the expected hours available to accomplish a given task can be substantially less than the calendar time available or the economic span of time determined by biological considerations.

The hours worked during a favorable fieldwork day can vary considerably. Younger men, short of capital, are usually prepared to substitute leisure and even sleep for machinery capacity, and may spell each other to keep the machines working 24 hours a day.[9] Also, farm workers may have other chores or duties which consume some portion of every working day. Simple operator preference (e.g., working on Sundays) or labor agreements may also have a bearing on how many hours are available for a tractor to operate. Thus, the total time available within a given period reflects physical constraints (the effects of weather on field conditions and the number of hours in a day) and other constraints (the desired allocation of available labor to machinery operations and worker preferences) as well as extra margins imposed by uncertainty.

Summary of Theoretical Considerations

In many ways the typical crop farming operation fits the standard microeconomic concept of the producing firm operating in a market environment of perfect competition. The farmer makes a decision about his intended level of production based on what he knows about his own production functions and according to factor and product prices over which he as an individual has little or no control. Given the profit function, marginal analysis can be used to determine the optimum allocation of resources for the least possible cost of producing the most profitable level of output. The prices (costs) and productivity of tractors and implements are considered in determining the optimum level of production and levels of resources.

Total costs for the production process are a function of the resources included and the cost of securing and utilizing the resources. Having outlined the cost components of tractor and implement acquisition and use, the objective then is to select tractor and implement combinations such that the total costs of the cultivation practices predetermined in the production process are minimized.

There are however problems in directly applying standard economic production and cost theory to farm machinery selection. The production function is largely unknown but most certainly discontinuous. Discontinuity offers no serious problem conceptually, but it does complicate determination of an optimum input mix immensely. The marginal factor cost functions of farm machinery services are also not continuous (due to the partitioning of ownership and operating costs) or independent (tractors are a "shared" power source). For these reasons, "lumpy" factors such as machinery are given as classic examples of "rationally" operating in the irrational stage of production, at least in terms of a super-imposed continuous function.

A Model for Determining Optimal Machinery Complements

When a farmer invests in a system of machinery, he generally does so on the basis of a previously formulated plan--or schedule--of use. The plan is based upon his crop-production objectives, the cultural practices to be employed and expected climatic conditions. The investment decision and the plan which accompanies it thus establishes his long-range, or "strategic" posture. It may be impossible to adhere to the long-range plan during years of adverse weather conditions or other uncertainties. Thus, a second type of decision, "tactical," may occur during those bad years. Tactical decisions are much more difficult to analyze and they represent where the art, as opposed to the science, of farming is most apparent.

A model for machinery selection, at least implicitly, incorporates many assumptions concerning risk preference, utility preference, and profit motives, even though it may explicitly have only a cost-minimizing objective function. These other considerations are a part of the exogenously defined demands and constraints placed on the model and the decision alternatives available to the model. Risk preferences enter the model, for example, by setting the desired level of risk for a certain number of favorable fieldwork days to be available in a specified time period. A preference for the risk involved with custom operators responsible for some of the machinery requirements is given by whether the custom option is available to the model or at what discount. Utility preferences might be revealed by providing only certain types, sizes, or brands of machinery from which the model can select. Restrictions on the number of tractors which may be purchased or number of operators hired are other ways in which noneconomic managerial discretion can enter the model. The profit motive is also very much a consideration, though exogenous, in that it determines the total machinery service demands and their temporal allocation.

The relevant length of the planning horizon may be quite important, particularly when there are large differences in indivisibilities among investment alternatives (Barry, 1972). An economically relevant planning horizon is suggested as the planning time needed in order to make a decision for the first period (Boussard, 1971). In other words, the planning horizon should be of such a length that the addition of one additional period does not affect the investment decisions of the first period. It is also quite likely that the economically relevant planning horizon will differ from the manager's subjectively relevant horizon due primarily to risk preferences. An investment schedule contingent upon land becoming available for sale at the right time, location, price, quality and size of unit may be stymied if such an expectation does not materialize (Barry, 1972). Applying an economic criterion to research, one would expand the planning horizon of the model until the cost of adding one additional period is greater than the additional value of the "improved" solution one would expect to obtain. The latter rule is, of course, more restrictive than the former.

The planning horizon of the following machinery selection model is one year in length and expecting an infinite number of future periods having the same requirements, resources and investment alternatives to follow. The research cost of expanding the model to follow each machine from acquisition to salvage or replacement is, at present, prohibitive.

The Objective Function

The objective function represents the total average annual amortized cost of machinery services and related considerations and would therefore be minimized by the solution procedure. The objective function of the model can be mathematically represented by:

IMPLEMENTATION (OPERATING COSTS) + TRACTOR (OPERATING COSTS) + LABOR (COSTS)

$$\text{Min } C = \left[\sum_{k}^{NP} \left[\sum_{j}^{NR} \left[\sum_{j}^{NO} VCI_{ij} \cdot HI_{ijk} \right] + \left[\sum_{m}^{j} VCT_{jm} \cdot HZ_{jmk} \right] \right] + HW_k \cdot HRS_k \right] + YH \cdot PMEN$$

(TIMELINESS COSTS) + (CUSTOM CHARGES)

$$\sum_{i}^{NO} \sum_{k}^{NP} \sum_{\substack{m \\ (m \neq k)}}^{NP} TC_{ikm} \cdot TA_{ikm} + \sum_{k}^{NP} \sum_{i}^{NO} CR_i \cdot CW_{ik} +$$

IMPLEMENT (OWNERSHIP COSTS) TRACTOR (OWNERSHIP COSTS)

$$\sum_{i}^{NO} \sum_{j}^{NR} FC_{ij} \cdot M_{ij} + \sum_{j}^{NR} TFC_j \cdot TZ_j \qquad (2.28)$$

with: $k = 1,2,\ldots,NP$ for denoting the time periods (not necessarily consecutive, sequential, or independent) defined by the user,

$j = 1,2,\ldots,NR$ for denoting the ranks (sizes) defined by the user,[6]

$i = 1,2,\ldots,NO$ for denoting the machinery operations linked to a particular type of implement and defined by the user.

where: C is the total average amortized annual cost;

VCI_{ij} is the variable operating cost, excluding labor, of the i-th implement, size j, in dollars per hour;

HI_{ijk} is the total hour usage of the i-th implement, size or load level j, in time period k;

VCT_{jm} is the variable operating costs of the j-th size tractor, operating at the m-th load level, excluding labor, in dollars per hour;

HZ_{jmk} is the total hour usage of the j-th sized tractor pulling load level m equipment in time period k;

HW_k is the hourly wage or opportunity cost of machinery labor in the k-th time period, in dollars per hour;

HRS_k is the total hour usage of machinery labor used in time period k;

YH is the total annual wage or opportunity cost of "permanent" (nonhourly) machinery labor, in dollars per year;

PMEN is the discrete number of machinery laborers used during the year;

TC_{ikm} is the timeliness cost per acre of the i-th machinery operation to be transferred from time period k to time period m;

TA_{ikm} is the total number of acres of the i-th machinery operation to be transferred from time period k to time period m;

CR_i is the custom work rate for the i-th machinery operation in dollars per acre;

CW_{ik} is the total number of acres of the i-th operation contracted to custom operators in time period k;

FC_{ij} is the total average annual discounted ownership cost of the j-th sized, and i-th implement-type, in dollars per unit;

M_{ij} is the discrete number of units of the j-th sized and i-th implement-type in the selected machinery complement;

TFC_j is the total average annual discounted ownership cost of a j-th sized tractor in the selected complement;

TZ_j is the discrete number of size j tractors in the complement;

NP is the maximum number of time periods defined in the model;

NR is the maximum relative size (rank) of implements and tractors defined in the model; and,

NO is the total number of machinery operations linked to a particular type of implement and defined by the user.

Note that in the objective function, the total variable operating costs of tractors and implements are assumed linear with respect to use. With reasonable ex ante estimates of annual use (for the repair cost equation) this assumption fits actual experience reasonably well. Note also that the short-term machinery labor wage rate (purchased on an hourly basis) may vary with the time period. Discrete man-years of labor are charged on a yearly salary basis. Timeliness costs are assumed to be linear on a per-acre basis. Curvilinear timeliness functions may be handled by defining additional time periods and approximating the curves with successive line segments. Custom work is accomplished on a per acre basis and charged in a like manner. Implements and tractors are purchased in discrete units at an average annual discounted cost of ownership.

Constraints of the Model

The objective function is constrained by several considerations.

Matching Equipment to Operational Requirements

The operational requirements, defining the "work" which must be accomplished and for which the complement is supposedly being selected, are given via the operational requirement balance equations as follows:

$$\sum_{j}^{NR} a_{ij} HI_{ijk} + \sum_{\substack{m \\ (m \neq k)}}^{NP} (TA_{ikm} - TA_{imk}) + CW_{ik} \geq A_{ik} \qquad (2.29)$$

for all i, i = 1,2,...,NO; and,

k, k = 1,2,...,NP.

where: a_{ij} is the actual field capacity (1/HPA in equation 2.27) of the j-th sized, i-th implement, in acres per implement hour;

A_{ik} is the total number of acres of operation i given to be accomplished (subject to timeliness transfers) in timeliness transfers) in time period k; and,

other variables as previously defined.

Machinery service demands for a particular time period enter the model via the right-hand side of equation (2.29). These demands are met either by "hiring" custom operators, or "transferring" the demand to another time period, or by operating an implement, or a combination of any of the three. The amount of machinery service accomplished in a particular time period may, of course, be greater than A_{ik} if there is a net flow of "work" from other time periods.

The productivity of the implement in acres covered per hour (a_{ij}) is the inverse of equation (2.27) and a function of the effective travel speed of the implement, its width, and field efficiency. For an implement of given size and field efficiency, increasing the effective speed of the implement increases its productivity or capacity. However, most implements must be pulled in narrow speed range to produce the desired results. Higher speeds can cause problems with accelerated wear, operator ride and control (Zoz, 1973). Slower speeds are harder on the tractor (Bowers, undated(a)). Whether a tractor pulls a wide implement at a slow speed or a narrow implement at a faster speed, the productivity per hour and the horsepower used is about the same, so oversizing is really impractical from a capacity standpoint. There are, however, two major advantages to sacrificing implement width for faster field speeds: (1) less ballast is required on the tractor and, (2) reduced strain on clutches, transmissions, axles, etc., due to reduced torque. Thus, there is not a great deal to be gained by having the mo-el select the implement speed from among a number of defined alternatives for an implement of given size.

Matching Tractors to Equipment

Machine implements do not accomplish tillage tasks by themselves, but must be provided power and locomotion by suitably powerful tractors. For every hour an implement is used, the pulling tractor must also be operated at least one hour. In fact, due to the time lost attaching the tractor to the implement, driving the combination to the field and other factors, the tractor may be operated somewhat more than one hour per hour of implement. A set of constraints which forces the model to balance tractor hours with implement hours is as follows:

$$\varepsilon_1 \sum_{i}^{NO} HI_{ijk} - \sum_{n=j}^{NR} HZ_{nqk} \leq 0 \quad \text{where } q = j \text{ and} \qquad (2.30)$$

for all

j, $j = 1,2,\ldots,NR$; and,

k, $k = 1,2,\ldots,NP$.

where: ε_1 is the conversion multiplier for transforming implement usage, in hours, to tractor hours (e.g., $\varepsilon_1 = 1.1$); and other variables are as previously defined.

In equation (2.30), the i-th implement of size j hours of use can be balanced only by tractors of size j or greater. Implicit then is that a large tractor is a perfect substitute for a smaller one. Implements can be "pulled" (at a given constant speed) either by a tractor just barely powerful enough or one much larger (i.e., a tractor cannot gear-down and pull larger implements at lower speeds, or up-gear and pull smaller implements at faster speeds than given). The ranking of the implements and tractors into a consistent array such that all implements of size j are pullable by size j tractors or larger is accomplished exogenously by the user.

Diesel engines now installed on most field tractors provide excellent part load fuel economy. Throttling back in higher gears for those situations where the tractor is pulling lighter loads than its rated capacity can provide substantial fuel savings (Bowers, 1978). Since fuel costs are a major item in the variable operating cost of a tractor, operating costs (VCT_{jm} in equation (2.28)) are differentiated by the load level. Therefore, the hours used in each period k are also differentiated by tractor size and load level. A tractor's load level cannot be greater than its ranking in size.

Matching Time Required to Time Available

The time available for performing various operations is limited, if by nothing more than the number of hours in a year. The number of hours a certain implement or tractor type that can be allocated (assuming operators are available) depends on the number of hours available in the time period for one machine's use multiplied by number of machines of that particular type available in the machinery complement. If a particular implement or tractor is used (i.e., hours consumed) in satisfying the given machinery requirements, this constraint provides that a suitable number of those machines are purchased into the complement.

The time-available balance equations are as follows:

for tractors;

$$\sum_{m}^{j} HZ_{jmk} \leq TZ_j TA_k \varepsilon_2 \tag{2.31}$$

for all j, j = 1,2,...,NR; and,

k, k = 1,2,...,NP.

and,

for implements;

$$HI_{ijk} \leq M_{ij} TA_k \tag{2.32}$$

for all i, i = 1,2,...,NO;

j, j = 1,2,...,NR; and

k, k = 1,2,...,NP.

where: TA_k is the number of hours favorable ("available") for machine operation in time period k;

ε_2 is a correction factor to allow some portion of the tractor hours surcharge (i.e., ε_1) to be done during "inclement" times (e.g., $\varepsilon_2 = 1.05$); and, other variables are as previously defined.

Equation (2.31) states that the number of hours used of a particular tractor size j and in each time period k totaled over all load levels must be less than or equal to the number of tractors of size j in the complement (TZ_j) times the time available in period (TA_k). The correction factor, ε_2, provides, in effect, additional time during the period for tractors for adjustments and time-loss which might be done outside the favorable hours available. Thus, ε_2 counteracts to some extent the impact of ε_1 in equation (2.30).

Similarly, equation (2.32) states that the number of hours of use of a particular implement of size j must be at least matched by the number of the j-th sized implements times the time in period k available for machinery operations.

In satisfying these two sets of constraints, the model determines a feasible set of implements and tractors which can accomplish the given operational requirements.

Matching Labor Requirements to Labor Availability

Unlike the other variable operating cost components, short-term machinery labor wage rates are allowed to vary between time periods to reflect differing direct or opportunity costs of labor. Also, in order to place special restrictions on the hiring of labor without restricting the use of the other variable components, labor is not included (as it sometimes is) in the hourly variable costs associated with direct machinery usage. The total amount of machinery labor required in a time period is equal to the sum of the tractor hours used multiplied by a factor which considers the additional time required to prepare and maintain a tractor. The demand for labor is satisfied by purchasing hired and operator labor on either a short-term hourly or annual salary basis or by using any available "free" labor.

The labor balance equations are generalized as follows:

$$\left\{\sum_{j}^{NR} \sum_{m}^{j} \left[\varepsilon_3 \cdot HZ_{jmk}\right]\right\} - HRS_k - PL_k \cdot PMEN \leq FL_k \qquad (2.33)$$

for all k, k = 1,2,...,NP.

Where: ε_3 is the conversion multiplier for transforming tractor usage, in hours, to machinery labor hours (e.g., $\varepsilon_3 = 1.1$);

PL_k is the hours available from annual employees in time period k; and,

FL_k is the hours of "free" labor available in time period k; and, other variables as previously defined.

Managerial Constraints

Some managerial constraints other than those quantified in economic or physical terms are involved with farm machinery complement selection. One of these constraints might be the desire or necessity of placing a maximum on the number of short-term or annual machinery operators available to "run" the complement. Certainly, a three-tractor complement which has all tractors in the field at once does not answer the one or two-man farm's machinery selection problem. A number of short-term operators constraint is given by:

$$HRS_k \leq TA_k \text{ NOP } \varepsilon_1 \; \varepsilon_3 \tag{2.34}$$

for all k, k = 1,2,...,NP.

Where: NOPS is the maximum number of short-term operators allowed in the solution; and,

other variables are as previously defined.

A number of annual operators constraint is given by:

$$PMEN \leq NOPA$$

where: NOPA is the maximum number of annual operators allowed in the solution; and,

other variables are as previously defined.

By the same token, the maximum number of tractors allowed in the solution might also be constrained at the decision maker's discretion, as the following number of tractors constraint provides:

$$\sum_{j}^{NR} TZ_j \leq MAXT \tag{2.35}$$

where: MAXT is the maximum number of tractors to be allowed in the complement; and,

other variables are as previously defined.

"Common Sense" Constraints

Some constraints tend to aid the solution algorithms with "common sense." For example, equation (2.36) adds the intuitive logic that for every defined operation there must be at least one of that particular type of implement in the solution complement or a custom activity defined.

$$\sum_{j}^{NR} M_{ij} + \sum_{k}^{NP} CW_{ik} \geq 1 \tag{2.36}$$

for all i, i = 1,2,...,NO.

Equation (2.37) provides that there will never be more implements of a particular type than there are tractors in the complement.

$$\sum_{j}^{NR} M_{ij} \leq \sum_{j}^{NR} TZ_j$$

for all i, i = 1,2,...,NO.

Adding such information to the model allows the solution procedure to short-cut nonsensical alternatives, reducing the computer time and resources required to reach a solution.

Activity Bounds

Numerous other constraints or bounds can be applied to the activity variables already defined in the model. For instance, if a used piece of machinery is available for selection (retention) and use at its salvage value, a bound would need to be placed on that particular activity at the level reflecting the maximum number of these machines available for retention. Another might be where a farmer wishes only to consider "optimal" selection of a part of his machinery complement but still realizes the great interdependencies involved with the complete complement. In this case, one would fix at a certain activity level those machines whose selection are to be left out of the analysis and leave relatively unbounded those machinery alternatives from which a choice of complement is needed.

Summary of the Model

The mathematical model presented (equations 2.28-2.37) combines several relatively unique features. First, the complement is constructed from a list of farmer-available implements and tractors provided by the user and incorporating any pre-solution discrimination. Secondly, the user matches and ranks the machines to provide tractor-implement compatibility. Thirdly, the total annual tillage requirements for a particular farm enterprise mix is divided into many time periods, each with its own hours-available constraint and timeliness considerations.

A particular implement-type operation can appear in any number of these time slots; possibly competing in each period with a different mix of other required functions for the shared tractor's operating time. Other alternatives, such as the availability of custom operators, and other constraints, such as limiting the maximum number of machinery operators or tractors, are easily incorporated into the decision model.

Pictorial Representation of the Model

Figure 8 displays a pictorial representation of a relatively small-scale machinery selection model. This "picture" of the model, formulated as a mixed integer, linear programming matrix shows a machinery selection problem involving one time period and one sub-period operation (implement type), three ranks (three sizes of each implement and tractor are available for selection) and with timeliness and custom activities defined.

The logical flow of the model begins with the primary operational requirements entering the model exogenously as the right-hand sides of rows 16 and 17 (Figure 8) and thus violating the constraint since the lower bounds and beginning levels of the implement operations, timeliness transfers, and custom work activities are set at zero. Suppose that a set of implement operation activities (columns 1-6) are selected to enter the basis (assume nonzero positive activity levels) to satisfy the operational constraint. The positive level of the implement operation activities causes the implement hours available constraints (rows 6-11) and the tractor-implement total hours constraints (rows 2-5) to be violated. The "purchase" of the specified implements whose hourly use satisfied the operational requirement (i.e., the M_{ij} columns (19-24)

	Implement Operations						Tractor Operations											Integer Activities											
	HI11K	HI12K	HI13K	HI21K	HI22K	HI23K	HT11K	HT21K	HT22K	HT31K	HT32K	HT32K	HRS.K	CW1.K	CW2.K	TA1KL	TA2KL	PMEN.	M11..	M12..	M13..	M21..	M22..	M23..	TZ1..	TZ2..	TZ3..		RHS
Objective Fn. (1)	a	a	a	a	a	a	b	b	b	b	b	b	c	d	d	e	e	f	g	g	g	g	g	g	g	g	g	N	
TrIm0K (2)	i	i	i	i	i	i	-1	-1	-1	-1	-1																	$\le$	0
TrIm1K (3)	i			i			-1	-1		-1																		$\le$	0
TrIm2K (4)		i			i				-1		-1																	$\le$	0
TrIm3K (5)			i			i						-1																$\le$	0
Im11K (6)	1																		-j									$\le$	0
Im12K (7)		1																		-j								$\le$	0
Im13K (8)			1																		-j							$\le$	0
Im21K (9)				1																		-j						$\le$	0
Im22K (10)					1																		-j					$\le$	0
Im23K (11)						1																		-j				$\le$	0
Tr1K (12)							1																		-k			$\le$	0
Tr2K (13)								1	1																	-k		$\le$	0
Tr3K (14)										1	1	1															-k	$\le$	0
LaborK (15)							m	m	m	m	m	m	-1					-n										$\le$	FL
Oper1K (16)	p	p	p											1		1												$\ge$	A_{1k}
Oper2K (17)				q	q	q									1		1											$\ge$	A_{2k}
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27		28

Figure 8. A Pictorial Representation of the Model as a Mixed Integer Programming Matrix

enter the basis at a positive level) satisfies the implement hours constraints. The hourly use of suitable sized tractors (the HT_{ijk} columns (7-12)) enters the basis to satisfy the tractor-implement total hours constraints. But, the tractor usage upsets the tractor hours available constraints (rows 12-14) which is relieved as tractors are purchased (TZ_j columns (25-27) enter the basis). The tractor usage also creates an excess labor demand (row 15) which may be relieved with the purchase of hourly labor (HRS_k), annual labor (PMEN), or available free family labor (FL_k).

Alternatively, the primary operational requirements (A_{ik}) could be satisfied by purchasing custom work (CW_{ik} column) or by transferring the requirements to another period (at a timeliness cost) where machinery resources and time are more available. A solution procedure for this type of model would evaluate alternative bases (sets of alternative non-zero activities) until the objective function could not be reduced any further.

A multi-period machinery selection model would be block diagonal in matrix design except for the inter-period links involving timeliness transfers and, of course, the shared implements, tractors and annual labor. Figure 9 displays a block diagram of a three period model. Note that rows 2 through 17 and columns 1 through 17 in Figure 8 would represent blocks A, B, or C in Figure 9. Also in Figure 8, columns 18 through 27 would be block D, row 1 would be block F and column 28 would be block 9, in Figure 9.

Data Requirements of the Model

The volume of data required by the model is quite large and presents a major problem of maintaining a complete and up-to-date machinery infor-

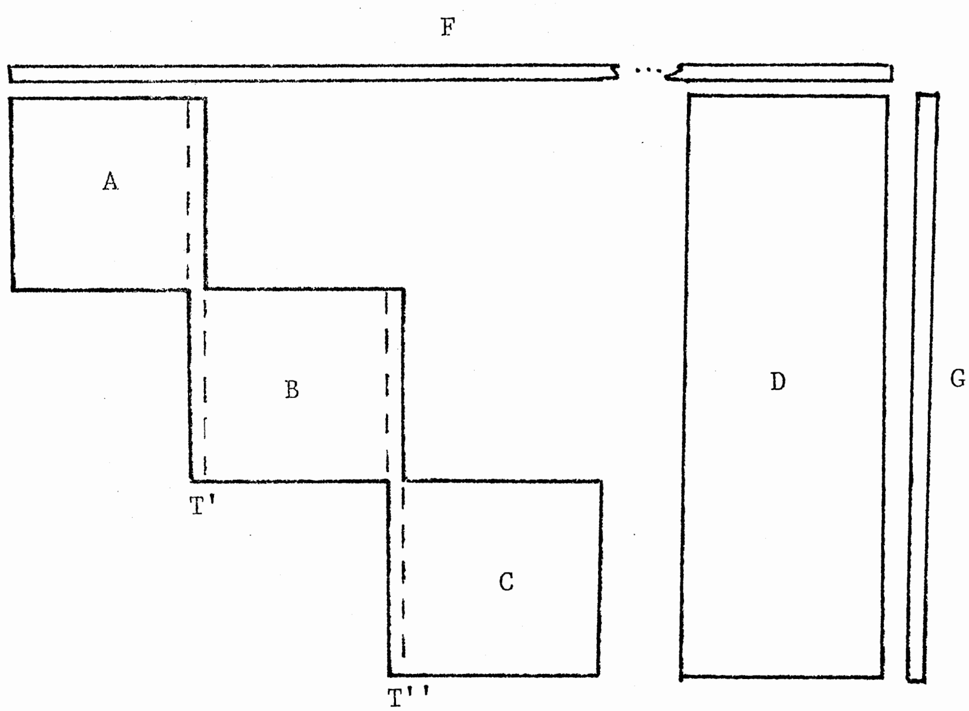

Figure 9. A Block Diagram of a Three-Period Model

mation data bank. Many of the machinery cost equations have been developed with computational ease and a minimum number of parameters as much the objective as accuracy. The sure-cure is complete and detailed farm machinery records. The application of any decision model is only as good as the quality of the factual data underlying it. The decision model, an example of methodological knowledge, is only a framework for analysis. It is up to the user-decision maker to feed it properly and use it well.

In gross terms, the data needed to accomplish a machinery complement solution are few, and can be broken down as follows:

(1) The enterprise mix with machinery operation requirements organized into time periods.

(2) Suitable hours available in each time period to accomplish machinery service demands.

(3) Set of machinery alternatives.

(4) Timeliness cost functions.

(5) Special parameters settings and other restrictions.

Shortcomings and Limitations of the Model

Since the model is a "model," it necessarily abstracts and simplifies reality and thus, some shortcomings and limitations will always be present. Further research and development will reduce or eliminate some of the shortcomings and limitations. Decision makers, however, should know the weakness as well as the strengths and unique capabilities of a model if proper use and application are to be achieved.

One of the shortcomings or limitations of the model is its handling (or lack thereof) of risk and uncertainty in a variety of forms. Using a single-valued set of expectations for suitable field days or desired cultivation practices produces a single value for total machinery costs. However, nearly every farming enterprise has a probability distribution of expected outcomes, as well as, an expected mean value (or mean value weighted by risk preference). A machinery complement which minimizes cost for one "average" year may be much too large or much too small in another year. If adverse weather eliminates the need for some operation one year out of five, a complement which accomplishes four-fifths of the requirement in a least cost manner may not be very good for either outcome.

Opportunities to select a more flexible (in terms of cost incidence over a range of operational requirements or time available) machinery complement are not explored by the model. For example, assume three different machinery complements each with an average annual cost of C_0 at X_0 (Figure 10) and C_0 is the lowest attainable cost of all possible machinery complement combinations. The model would not be able to choose the best one from among the three. In fact, the model would choose the first one it found and finding none "better" (in a least-cost sense) would declare it optimal. If, in Figure 10, the model discovered complement II first and the operational requirements (or similarly the time available) were subject to considerable variability, then the decision maker might not have the best solution to his farm machinery selection problem. For example if the variability in X was symetric about X_0, then complement I would be the better choice. If the variability in X was skewed to the right of X_0, complement III would be the better. One possible remedy to this problem is to parametricly adjust X such that a number of model runs are made at various operational or time available

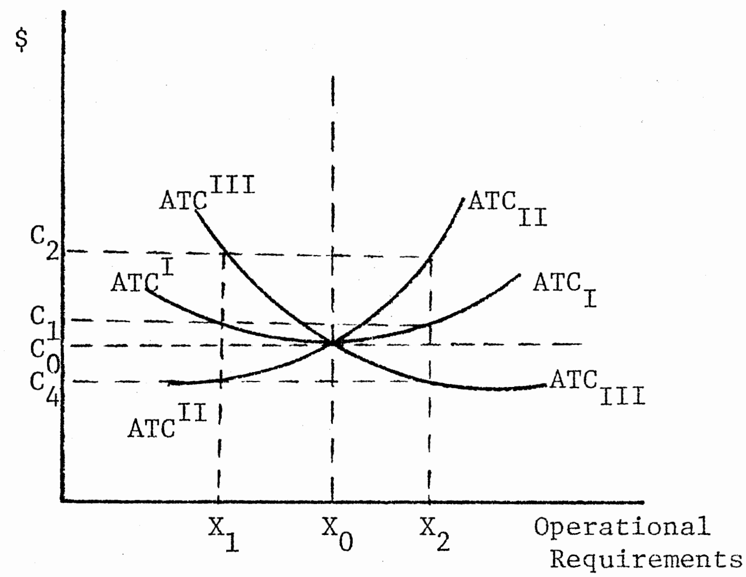

Figure 10. Average Total Cost Curves of Alternative Machinery Complements with the Same Average Cost at Point X_0

levels and then note the stability of the model's selected "optimal" complements.

Flexibility in the long run is also a desirable feature of machinery complements. Changes in relative input prices, relative output prices, and technology can change crop mixes, cultivation practices, and even tractor-implement combinations. Some complements are more adaptable than others.

Some types of costs, namely cash costs versus noncash items, may have different implications for risk than others. In the model, all machinery cost components are summed and treated equally.

There is also little consideration for income tax effects including the various tax incentives and disincentives involved with investment tax credits, depreciation schedules, and capital gains. A recent study by Edwards (1979) indicates, however, that income tax effects do not significantly affect the size of least-cost machinery complements, though it does tend to reduce the estimated variability of total costs from year to year (i.e., the tax system made average total cost curves longer and flatter).

The operational requirements of the model (the sum of the total acres of each cultivation practice) are determined exogenously and thus must be met with the resulting cost open-ended. Machinery selection, crop selection (including alternative practices), and job scheduling are interrelated and require an integrated planning process. The simultaneous consideration of optimally selected crop plans and machinery selection and scheduling has total gains greater than sum of the gains from separate optimization (Danok, McCarl and White, 1978). One obvious remedy is to include crop production activities in the model. Another remedy would be to create a crop production system release activity with a "cost" set at the maximum allowable machinery expense per acre outside of which the set of operational demands would be changed.

The investment capital requirements, cash flow requirements, and other financial aspects of acquiring and using farm machinery are not included in the model as factors in determining optimal machinery complements. In reality, many farmers face financial constraints in selecting farm machinery.

Lastly, the model does not trace the time path of a currently existing machinery complement evolving toward an "optimal" one or provide insights into optimal machinery replacement.

Summary of the Chapter

In this chapter the basic reasons for building a model to use in machinery selection decision-making, and for basing its foundations firmly in economic theory were discussed. A review of relevant economic principles in production theory was given and the problems involved with applying it directly to machinery problems. The relevant cost components of machinery management were described and a selection model formulated. A mathematical model for determining optimum farm machinery complements and scheduling their use was presented and relevant variables defined. Some of the limitations and shortcomings of the model were also discussed.

FOOTNOTES

[1]The economics of economic research is ironically an almost totally neglected area.

[2]It is clearly much easier for the theoretician to manipulate mathematical functions, such as x/ v than it is for the empiricist to quantify them in real numbers.

[3]The input price function is assumed to be constant (i.e., $w_i = g(x_i) = \bar{w}_i$). Note also that this condition is independent of the revenue function of the firm and must hold not only at the final point of optimal output but at every point on the cost curve.

[4]Some of this extra equipment can be economically justified in terms of operator safety or lessening fatigue so longer hours or other productive work can be accomplished.

[5]The factor inputs M, O and T are operationally combined into cultivation practices (x_i) which are themselves inputs into the crop production process.

[6]In these inflationary times, many farmers are finding their old and worn-out machinery worth more at trade-in than their original purchase price. This does not, however, eliminate the need for a depreciation charge or, perhaps more appropriately named, a capital replacement allowance.

[7]The appropriate discount rate can be adjusted for taxes and inflation by the formula:

$$r' = \frac{1 + r(1-MTR)}{1 + g} - 1$$

Therefore, a 10 percent before-tax discount rate (r) becomes a 1.13 percent deflated after-tax discount rate (r') under a 6 percent rate of inflation (g) and a 28 percent marginal tax rate (MTR) (Watts and Helmers, 1978).

[8]One horsepower delivered for one hour is one horsepower-hour of energy. The type of horsepower used in calculating horsepower-hours is PTO horsepower.

[9]Working long hours or at night can, however, significantly reduce the effective capacity of the equipment, perhaps a negative amount if avoidable accidents and breakdowns occur.

CHAPTER III

SOLUTION TECHNIQUES FOR MIXED INTEGER PROGRAMMING PROBLEMS

Introduction

Questions involving discrete decision making have often been asked by agricultural economists. Numerous decision making or planning problems in agriculture involve "noncontinuous" costs or "lumpy" supplies of inputs. It is not hard to view a largely nonlinear world and notice how awkwardly general linear programming with its assumptions of linear and infinitely divisible activities attempts to approximate it.

Algorithms to solve linear programming models have advanced far since the invention of the simplex method by Dantzig and others during World War II. LP models ranging in the hundreds of thousands of activities and tens of thousands of constraints have been successfully solved. In fact, as far as "straight" linear programming goes, the algorithmetic procedures have greatly outpaced the modelers' ability to feed such models' gigantic appetites for data (Orchard-Hayes, 1968).

Nonlinear programming procedures are not as advanced. Recent developments in solving quadratic programming models are encouraging, but still limited. Developments in the use, computational aspects, and theory of integer programming have been substantial (Geoffrion and Marsten, 1972). But, only some measure of success has been achieved in solving the rich variety of integer programming models of real problems. Problem size is still a major limitation.

Linear Programming

For more than two decades in land grant universities, new farm management appointees have been capable of expressing decision problems in a mathematical programming framework. Many undergraduate programs have for several years introduced linear programming topics in farm management courses. In fact, it is hardly necessary to justify the use or define the technique known as linear programming. Innumerable articles and chapters on linear programming have appeared in print as its use has spread through the scientific disciplines. Linear programming also has had a close association with computers, having grown up with them simply because of LP's enormous requirement for arithmetic and data manipulation (Orchard-Hayes, 1968).

The Simplex Method

The idea of the simplex method to solve linear programming problems is to proceed from one basic feasible solution (i.e., one extreme point of the convex set) of the constraint set of the LP problem to another, in such a way as to continually decrease (increase) the value of the objective function until a minimum (maximum) is reached. For an LP problem with n activities and m constraints, the optimum solution will occur at a point for which at most m variables have positive values. Usually, the solution set of activities will have exactly m positive values. The remaining (n-m) variables will be zero. Each set of m variables is called a basis. Thus, we could take various bases of m variables, set the remaining variables to zero, and solve the resulting m equations and m variables (unknowns). However, there are $n!/[(n-m)!m!]$ or $\binom{n}{m}$ possible bases (alternative sets of m variables) and this can be a very large number.

Extension experience with the simplex procedure applied to problems from various fields, and having various values of n and m, has indicated that the simplex method can be expected to converge in about m, or perhaps 3m/2, pivot operations (basis changes).

The revised simplex method is a scheme for ordering the computations required of the simplex method so that "unnecessary" calculations are avoided. A further variant of the revised simplex method is used in most commercial LP packages and is based on a product-form representation for the inverse of the basis matrix. This variant often requires fewer computations than other methods, but its primary advantage is its minimal high speed core (i.e., computer memory) requirements.

Mixed Integer Linear Programming

A mixed integer linear programming problem is a linear programming problem "further constrained." The additional constraints being that some or all of the real activities must have discrete activity levels. None of the nice mathematical properties which depend on the convexity of the feasible region carry over to this class of problems. Further, it is not possible to examine a proposed solution in isolation to see if it satisfies conditions for optimality--a locally optimal point has no guarantee of being globally optimal. Discrete programming problems are at least an order of magnitude more difficult to solve than LP problems of comparable size.

If we attempt to solve integer linear programming problems via the simplex procedure (treating it as a general linear programming problem) and produce a suitably integerized solution, we clearly have the optimum solution to the original integer problem. In some cases, the simplex algorithm does indeed produce mixed integer solutions. However, when this does not occur and when the mixed numbers solution values are small (less than 30), rounding or truncating the fractional part, to produce an "integer" solution, may not be anywhere close to the optimal integer solution. In many problems, the "continuous" LP solution, ignoring the discrete constraints, is quite meaningless.

The main difficulty with integer problems is that one must move in discrete steps. In continuous problems, a single variable can be selected and moved continuously until some constraint is reached, then another selected and moved, and another, until optimality is achieved. The linear programming theorems assure that the optimal solution, assuming it exists and is finite, can be represented in no more than m (the number of constraints) variables. However, as soon as one requires integer valued variables, these underlying principles cease to hold. In general, it is not possible to represent any feasible integer solution, let alone the optimal one, as a basic solution. The example shown in Figure 11 illustrates this point. The optimal continuous solution (with an objective to maximize x + y) is at (3.5,4) with a value of 7.5. The optimal integer solution is at (4,3) with a value of 7. The only extreme points with integer values are (0,0) and (6,0). Hence, these are the only lattice points which have basic solutions. Note also that in going from (3.5,4) to (4,3), one variable increases and the other decreases. Hence, in higher dimensional space, enumeration of feasible lattice points in the vicinity of the continuous optimum is impractical. Only two values each for 100 variables gives 2^{100} combinations. There is, of course, no assurance that a feasible lattice point lies within any given number of units from the continuous optimal solution for every integer variable.

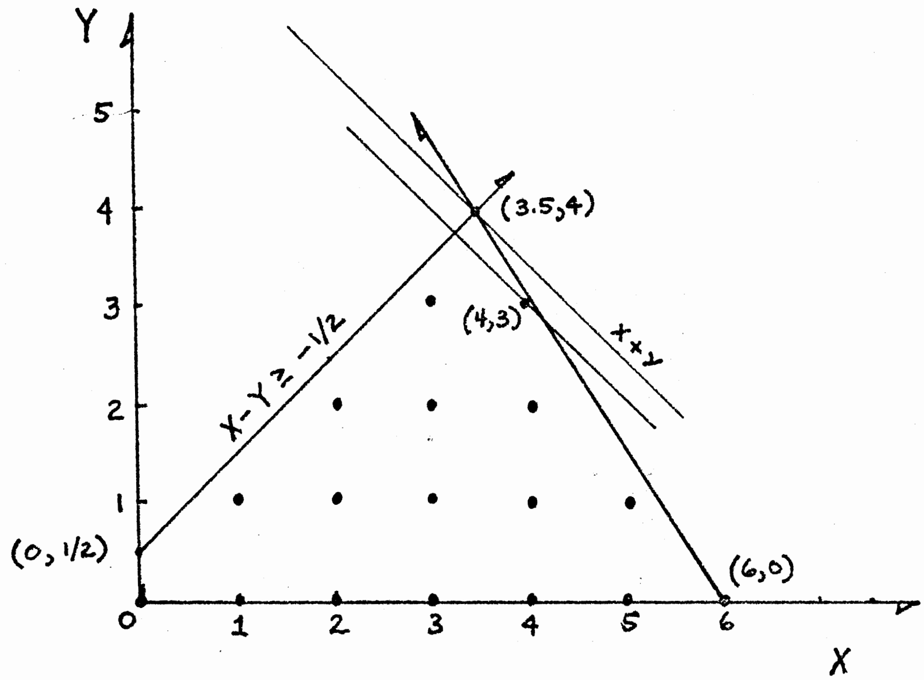

Figure 11. Graphic Solution of a Continuous and Integer Linear Programming Problem

The Cutting Plane Method

Dantzig (1957) first presented the so-called "cutting-plane" method for solving problems which require integer solutions to all variables. This method consists first of solving the linear programming problem without integer constraints. If the optimal solution satisfies the integer conditions, the solution is final. If not, additional linear constraints, called cutting planes, are added to the model in a manner to "remove the nonadmissible extreme point solution and yet retain all admissible solutions" (e.g., those having integer values) (Dantzig, 1957). The model is resolved and further cuts made until eventually all the basic solution variables have integer values. It was, however, Gomory (1958a) who developed a theory of automatically generating "cutting planes" with a proof of an integer solution in a finite (though, it may be large) number of steps. Gomory's method was further generalized to include mixed integer programming problems, as well (Gomory, 1958b).

If a cutting plane algorithm is going to solve a given problem in a reasonable amount of time, it tends to solve the problem with relatively few cuts (Garfinkel and Nemhauser, 1972). Although the algorithm has been proven to converge in a finite number of cuts, the actual number of cuts required may be too large to be of practical value.

A second comment about cutting plane algorithms is that fairly sophisticated computer programming may be required to cope with the round-off error. Programming techniques such as double precision arithmetic help reduce this problem of round-off error; it cannot be completely avoided. If a cut is developed with improper integrality decisions, the optimal solution may not be correctly identified by the algorithm.

The cutting-plane technique also may tend to get "stuck" at some value of the objective function (Land and Powell, 1973, p. 169). It is not inconceivable that hundreds of successive cuts may leave the value of the objective function substantially unchanged. A large number of cuts also increases round-off error, which may make a good solution obtained after a large number of cuts unbelievable.

An additional aspect of the cutting-plane technique is that some things which may appear trivial may make a substantial difference in search time for convergence. For instance, although it is algebraically true that $X_1 \leq 10$ is algebraically the same as $2X_1 \leq 20_1$ the cutting-plane algorithm will not necessarily react the same to each of these constraints.

The cutting plane algorithm is a "dual" method, because it starts with an infeasible solution (the LP solution) and proceeds to search for a feasible solution. The first feasible solution to the integer problem is also the optimal solution. This has the disadvantage that if the computer time available is not sufficient for convergence, no workable solution is available for the time spent (Land and Powell, 1973, p. 173).

Sometimes, the modeler already has an integer solution which might be optimal and needs only to verify or disprove its optimality. It is not easy to adapt the cutting plane method to this kind of problem or use this information as a short-cut toward an optimum solution.

Algorithms based exclusively on cutting planes have not in general, been effective. Although it is sufficient to generate the convex hull associated with the feasible points it is not necessary. In fact, generating the convex hull is usually far too laborious. It is sufficient to make the optimal integer solution an extreme point and remove all noninteger extreme points with a better objective function value. Thus the emphasis in the search for practical computational methods has switched to branch and bound and other decomposition approaches (Geoffrion and Marsten, 1972).

Benders' Decomposition

In 1962, Benders proposed a partitioning approach for solving programming problems that involve a mixture of either different types of variables or different types of functions. As applied to mixed integer problems (the former case), the Benders approach decomposes the problem into two separate problems (McDaniel and Devine, 1977). Global optimality of the overall problem is attained through the use of dual information. In general terms, the approach is iterative, where a solution is proposed by a master (integer) problem then tried in the (linear) subproblem, which returns dual information to the master problem. The master problem then chooses a new solution based upon the duality information of this and all previous subproblems. The new master problem solution is then returned to the subproblem and iterations proceed. Termination of the procedure occurs due to bounding conditions. At each iteration involving the master problem the procedure gives a best possible objective value that could be found, and at each subproblem iteration the actual objective function is computed. These outputs yield a monotonically nonincreasing bound spread, indicating the maximum difference from optimality (Danok, McCarl, and White, 1978).

One drawback to this method is that it requires solving a "pure" integer problem (usually by a cutting plane algorithm) at each iteration. The true usefulness of Benders' algorithm thus depends heavily on the efficiency of the integer programming algorithm used to solve the pure integer master problem. An attractive feature of this algorithm is the availability of upper and lower bounds on the optimal objective value, which both converge as optimality is achieved. However, the Benders' method is not an integer solution technique itself, but a hybrid combining IP and LP procedures to solve large-scale MIP problems.

The Branch-and-Bound Method

Since any bounded mixed integer programming has only a finite number of feasible solutions, it is natural to consider some kind of enumeration procedure for finding an optimal solution. Unfortunately, this finite number can be, and usually is, very large. Despite the fact that current generation computers can perform as many as one million elementary arithmetic operations per second, exhaustive enumeration would be prohibitively time-consuming for problems of any practical size. Therefore, it is imperative that any enumeration procedure be cleverly structured so that only a tiny fraction of the feasible solutions actually need be examined.

The basic idea of the branch-and-bound technique as pioneered by Land and Doig (1960) is the following. Suppose that the objective function is to be minimized. Assume that an upper bound on the optimal value of the objective function is available. (This usually is the value of the objective function for the best feasible solution identified thus far.) The first step is to partition set of all feasible solutions into several subsets, and, for each one, a lower bound is obtained for the value of the objective function of the solutions within that subset. Those subsets whose lower bounds exceeds the current upper bound on the objective function are then excluded from further consideration. One of the remaining subsets determined as the "most promising", say, the one with the smallest lower bound, is then partitioned further into several subsets. Their lower bounds are obtained in turn and used as before to exclude some of these subsets from further consideration. From all of the remaining subsets, another one is selected for further partitioning. This process is repeated again and again until a feasible solution is found such that the corresponding value of the objective function is no greater than the lower bound for any subset. In the process of partitioning, most of the feasible solutions are enumerated implicitly and only a few explicitly.

The branch-and-bound technique thus leads to successive optimizations of LP problems which in general can be illustrated in terms of a search "tree." A typical MIP tree is shown in Figure 12 and is composed of nodes and directed branches. The nodes are numbered in the order they are generated. One node can generate 0, 1, or 2 new nodes, which are called successors. An (ordinary) LP problem and its optimal solution are attached to each node. The LP problem attached to the node has the same constraints, except for the integrality conditions, and the same objective function as the given problem. The upper and lower bounds on the integer activities of the nodal LP differ from the original problem as structured by the tree.

In Figure 12, the origin (node 0) corresponds to the set of all feasible solutions. This set is partitioned into several subsets, usually by designating the respective values or partitioning the bound set of one of the integer variables. Each of these values or bound partitions corresponds to a node at the end of a branch out of the origin. Associated with each node is a lower bound on the value of the objective function

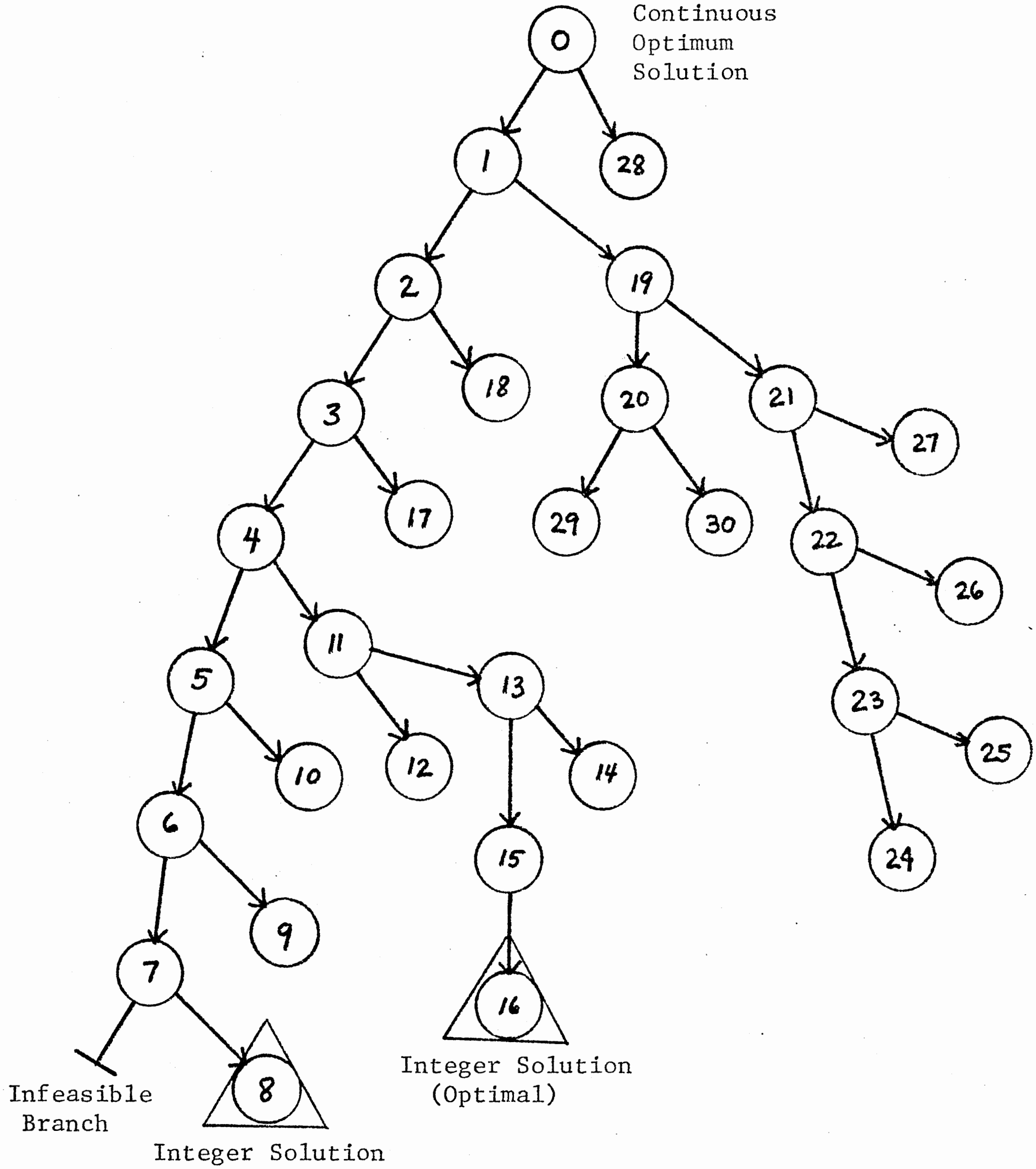

Figure 12. A MIP Search Tree

for the feasible solutions that can be reached from that node. One then branches (develops) from the origin to the node with (say) the smallest lower bound. The branches out of this node are constructed, and a lower bound obtained for the node at the end of each of these branches. From among all the nodes that comprise the end points of the tree, one with (say) the smallest lower bound, is chosen for constructing the next set of branches and associated bounds. This process of branching and bounding is repeated again and again, each time adding new branches or nodes to the tree, until the endpoint node having the smallest lower bound corresponds to a complete feasible solution. This solution is then known to be an optimal solution, and the development of the tree is completed. This branching process generates a "whole tree." Each terminal branch is either infeasible or points to an integer node.

It is not necessary, however, that the branching be done from the end-point node having the smallest lower bound. By always continuing from the node with the smallest lower bound, the total amount of tree searching is minimized since no branch is developed further than the best available alternative node. However, storage requirements could become prohibitive since there would be numerous eligible nodes awaiting further development and each eligible node is, in itself, a full-scale LP model. A considerable amount of searching and data transfer would also be required since the algorithm would need to evaluate each waiting node and may jump from one main branch to another at every development of a new node. Moreover, it takes a long time before the first integer solution is found. Attempts have been made to limit this kind of search.

One popular alternative is to consider only the most recently created set of nodes (i.e. only nodes on the "main branch" currently being developed would be considered). If there are no nodes which have a lower bound less than the current upper bound of the problem, then one backtracks into the tree until a suitable node for branching is found. Although this alternative procedure tends to require more iterations (since it tends to over-develop some branches of the tree), it also requires much less storage of previous calculations (since there are not as many awaiting nodes at any given moment), which is sometimes an important consideration for computer execution. A first integer solution is also usually determined fairly quickly. But when an integer solution is found, it is not immediately known whether it is optimal. The search must therefore continue until either a better solution is found or it is proven that no better solution exists. Occasionally, particularly for problems with many integer variables and relatively loose constraints, "good" solutions are quickly found, but a long computation is necessary either to improve them slightly or to prove their optimality.

There are three main properties of MIP search trees which are given here without demonstration. First, all subproblems attached to the nodes of a MIP tree are distinct. They differ by at least one bound constraint over one integer variable. Secondly, a MIP tree necessarily has a finite number of nodes if each integer variable is given a finite upper and lower bound. For example, in a MIP problem with p integer variables, all being 0-or-1 variables, the tree node number cannot exceed $2^{p+1}-1$. The minimum number of nodes which could be generated is 2p. Finally, a MIP tree is not unique--more than one tree can be attached to the same MIP problem if the choice of the branching variable at each waiting node is not unique.

An additional comment is that when an integer solution is found, the program does not examine whether the corresponding subproblem has other optimal solutions which are integer. The program does not automatically produce all integer solutions whose functional value belong to a given range (i.e. the possibility of "alternative optima" is not indicated or explored automatically as in LP).

The branch-and-bound technique is a "primal" algorithm. It starts with a feasible solution (or often finds one reasonably soon) and then attempts to improve upon this solution. Thus, a workable solution is often available if termination prior to optimality is required (due to limits on continous real-time execution, computer funding, etc.). Similarly, the branch-and-bound technique can be used to find a nearly optimal solution, generally with much less computational effort. This is done by merely terminating the procedure the first time that the smallest lower bound is within a prespecified percentage (or quantity) of the current upper bound (the value of the latest integer solution) for the problem. The feasible solution corresponding to the current upper bound is then the desired suboptimal solution such that the resulting value of the objective function is guaranteed to be within the prespecified amount of the optimal value. Many times continuing the algorithm only improves the "guarantee" and does not render any better integer solutions.

Major Differences Between Branch-and-Bound and Cutting Plane Methods

There are four major differences between the branch-and-bound and the cutting plane methods. (The benders' algorithm generally depends upon a cutting plane method.) First, in the cutting plane method, the cuts never eliminate from the feasible region any feasible integer solution. With the branch-and-bound method feasible integer solutions are frequently cut away and often even the optimum integer solution. Secondly, in the cutting plane method the cuts will not generally be perpendicultar to any of the axes as are the partitions in the branch-and-bound. Thirdly, in the cutting plane method, as cuts are added, the feasible region shrinks and the problem size expands (some variants allow nonbinding constraints to be deleted, though they might be regenerated later in the search). In the branch-and-bound method, no new variables or constraints are added by the procedure. Finally, as previously noted, the cutting plane method is a dual algorithm while the branch-and-bound method is a primal one.

"Binding" or "Tight" Constraints in Interger Programming

A constraint which is not tight or binding in the optimal solution of a continuous linear programming problem may be removed from the problem without affecting the optimal solution. Whether a constraint is binding is easily determined by the value of its slack variable. If the slack variable is nonzero, that constraint is nonbinding and is not affecting the optimal solution. This property does not carry forward to interger programming (Land and Powell, 1973, p. 171-2). The only way we can ascertain whether a constraint is affecting the problem is to solve the problem both with and without the constraint. If the answer changes, the constraint was tight (binding) even though its slack may have been positive at optimality.

The effect of a constraint becomes particularly important when the question of bounds for a variable is considered. Most branch-and-bound procedures require upper and lower bounds be defined for the interger variables. It is tempting to follow an erroneous logic in determining whether an upper bound was set high enough. If, for example, an upper limit is tentatively set at, say, 3 and if this variable turns out to have an optimal value of, say, 2 it could mistakenly be assumed that the bound was high enough. This can be shown by counter-example (Land and Powell, 1973, p. 172).

Parametric and Postoptimality Analysis

Postoptimality analysis and parametric optimization techniques are fully developed aspects of linear programming. Their value in practical applications is well established. In the context of integer linear programming, however, these aspects have barely begun to be developed (Geoffrion and Nauss, 1977).

Postoptimality analysis and parametric techniques for ordinary linear programming can be viewed in terms of recovering the standard termination conditions associated with the simplex method. The final tableau corresponds to an equivalent representation of the original LP problem. The termination conditions associated with a branch-and-bound method are of a different sort. There is no final tableau. Instead, there is an exhaustive partition of the solution space of the original integer programming problem along with proof that no cell of the partition can contain a feasible solution superior to the final incumbent (Geoffrion and Nauss, 1977).

Integer programming models therefore have no shadow prices or dual variables with an interpretation comparable to that in linear programming. In order to determine--even locally--the influence of varying a resource level on the optimal value, in general one must resolve the problem with alternative resource levels.

The absence of meaningful shadow prices in integer programming is a manifestation of a more general technical difficulty. Neither the optimal value nor the optimal solution of an integer program need be continuous as a function of the coefficients defining the constraints. Ordinarily this difficulty does not occur in linear programming, where small changes in the data lead to small changes in the results. This property is one of the reasons why LP models behave "reasonably" when resolved with alternative data values. Integer programming models, on the other hand, can behave in an erratic and unpredictable manner due to the presence of multiple discontinuities caused by (necessarily discrete) changes of value for the integer variables. It is therefore wise to conduct what might be called a "continuity" analysis study for most IP models in order to ascertain whether or not any discontinuities in the region of interest are large enough to diminish the usefulness of the numerical results (Geoffrion and Nauss, 1977).

Unfortunately, there is no one simple way of using a previous best integer solution to assist in finding the best integer solution to a slightly revised version of the original problem. The previous solution may allow a good beginning "cut-off" level to be guessed which may speed up the new search. A previous (non-optimal) integer solution may also be a feasible integer in the revised problem and perhaps an even better producer of a cut-off level for the revised problem. (Obviously, before one attempts to solve a "family" of MIP problems some consideration to the order in which they are solved can shorten solution times.) Of course, one can always (with hindsight) supply a priority list that will enable a given problem to be solved more easily. Whether the same guidelines could be successfully applied to a similar or related problem is uncertain, but probably worth investigation.

MIP Problem Formulation for Solution Performance

The way a problem is formulated has a significant influence on the ease with which it can be solved. It combinatorial models, it is often possible to modify the formulation in such a way that the integer part of the model is much more tightly constrained and hence the amount of branching is reduced.

There are several important differences in formulating LP and MIP problems for solution performance (IBM, 1973b). For instance, in linear programming, adding additional activities to the model makes little difference in the solution time of the resulting problem. However, in formulating MIP problems, the reverse is often true if the additional columns add integer variables. Similarly, in linear programming, adding additional constraints to a problem represents in an exponential increase in solution time. For MIP problems, if the additional constraints involve the integer variables the reverse is often true. In fact, the more constrained the MIP problem, the easier it is to solve.

Besides adding constraints, the order in which the integer activities are processed during the search is very important. The amount of computation needed to develop the "tree" depends very much on which variables are chosen to branch from at earlier nodes. It is better to evaluate "important" alternatives as early as possible in the search tree and in that way not have to re-evaluate an important decision (a much more time-consuming process) many times for various combinations of much less important variables. Highest priority might be given to sums of integer variables, the processing of which lead to infeasible branches and therefore a shortened tree.

IBM's MPSX-MIP Computer Software Package

Description of the Program Product

The Mathematical Programming System--Extended (MPSX) is an International Business Machines Corporation (IBM) Program Product that provides expanded capabilities over the earlier Mathematical Programming System (MPS/360) (IBM, 1973a). Some of these additional or improved capabilities include a substantially faster execution time, an expanded problem size of 16K rows, simplified output filing, and the optimal Mixed Integer Programming (MIP) feature.

MPSX and its supporting programs provide a mathematical programming system that includes a control program and control program compiler, a set of procedures for linear, separable, and mixed integer programming, and various matrix generation and report writing aids. The computer code is capable of solving continuous linear programming problems with up to 16,383 constraints. The MIP program logic is limited to a maximum of 4095 integer variables, but the realistic limit is very much smaller dependent on the specific problem type and structure (IBM, 1973b).

MPSX-MIP uses a branch-and-bound procedure for solving mixed integer programming problems (IBM, 1971). There are, however, many rules using different parameters controlling the search process (Benichou, Gauthier, Girodet, Hentges, Ribiere, and Vincent, 1971). In MPSX-MIP, the user has some control over the search procedure and therefore has some opportunity to improve solution performance on specially structured models.

Limiting the Search

Certain properties of MIP trees can be used to limit the search process. Limiting the search is effected by eliminating, either permanently or provisionally, the processing of waiting nodes which hold little promise of producing the optimum integer solution. To decide whether to eliminate a waiting node from consideration, it is necessary to estimate what results could be obtained should the search continue from that particular waiting node. Can an integer solution be produced from this node? If so, what is the functional value of the best integer solution that can be obtained? The MIP program provides two kinds of information related to the latter question--the optimal value of the node, or functional value of the node and the estimation of the node.

The functional value of a waiting node k gives concrete information about that particular node, but may be a poor indicator of the functional values of any successor nodes that might result from it. However, it is certain that any integer solution, and in particular the best one, obtained at a descendant node of node k will have a functional value no better than that of node k. It also follows that the best integer solution that can still be expected from the current set of waiting nodes cannot have a functional value better than the best functional value of the waiting nodes. Therefore the functional values of waiting nodes are mainly used for deciding whether to abandon them.

MPSX-MIP provides two cells (XMXDROP and XMXPOF) to allow the user to control this portion of the search (IBM, 1973b). If during the search a waiting node has a functional value worse than XMXDROP, the node is "dropped" since it is of no further interest. XMXDROP can be set at the beginning of the search (if, say, the functional value of a feasible integer solution is already known and integer solutions worse than the set value are not of interest) and dynamicly as better integer solutions are found during the search (e.g. XMXDROP is set to the functional value of each successively better integer solution or the functional value plus some amount).

XMXPOF ("Postponed due to Functional value") allows a waiting node which has a functional value worse than XMXPOF to be abandoned provisionally (postponed for consideration). This facility speeds up the search by avoiding the processing of waiting nodes considered to be of no interest now, but perhaps later. XMXPOF differs from XMXDROP by the absolute value of a cell called XMXSTEP. XMXPOF is better than XMXDROP since the candidate set of waiting nodes is a subset of the waiting nodes (Figure 13).

The MIP program also attempts to provide a more realistic indicator of the functional values of successor nodes by making simplifying assumptions about the behavior of integer variables in the model. A node estimation is only an indication and not an upper or lower bound of the functional value of the best integer solution that can be found at a descendent node. Periodically, waiting node estimations are recomputed using new information obtained as the search progresses; the deeper the tree is scanned, the more accurate the estimations should be.

In the standard MIP strategy, node estimations are optionally used in choosing each branching node. But, a waiting node can also be postponed (provisionally abandoned) if its estimation is worse than XMXPOE ("Postponed due to Estimation"). However, before using node estimations to limit the search it is highly recommended that previous searches in analogous models be examined because the reliability of node estimations depends on the model type.

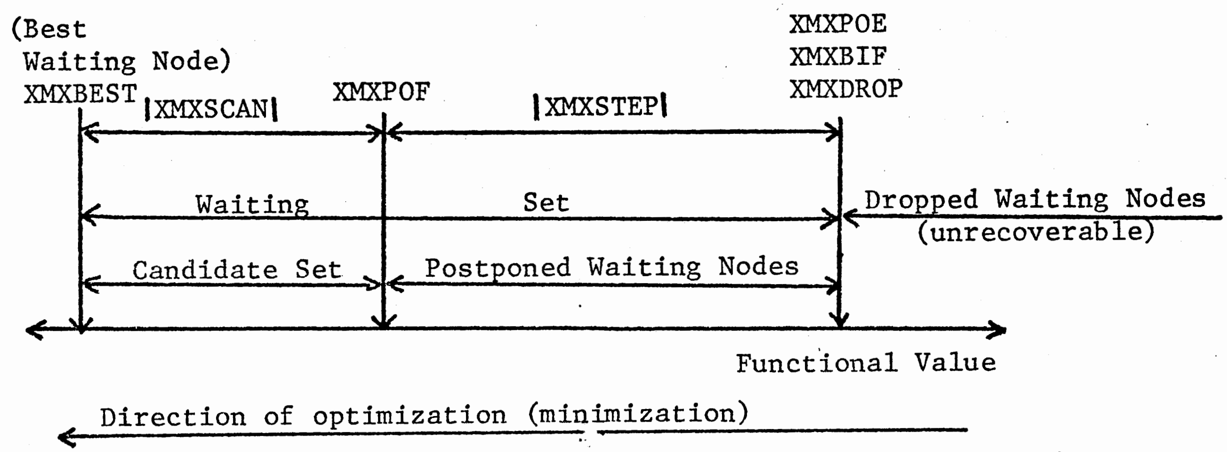

Figure 13. Map of Waiting Nodes in a Search

In summary, a waiting node is a candidate for further development if it meets three criteria. First, the node's functional value is better than XMXPOF. Second, its estimation is better than XMXPOE. And finally, the node is not otherwise defined inactive.

Choice of the Branching Variable

The choice of the branching variable is controlled by the tolerance value, XMXTOLI (XMXTOLI contains the fractional value [$0 \leq$ XMXTOLI < 0.5] which defines a quasi-integer value. A quasi-integer value is a value which differs from an integer by less than XMXTOLI) and a control switch, SW1. The branching variable is chosen from among integer variables without quasi-integer values. Switch SW1 defines the priority of the integer variables. If SW1 is equal to zero (the standard strategy), the branching variable is chosen according to a specified order, such as the order in which the integer variables are present in the matrix or decreasing order of their absolute cost values. If SW1 is equal to one, the branching variable is chosen using pseudo-costs of integer variables to get the greatest expected deterioration of the functional (Gauthier and Ribiere, 1977).

The choice of the next branching node is controlled by switch SW2 and SW3. If SW2 is equal to zero, the node chosen is the successor node (node n+1 or n+2) at the end of the branch for which the smallest pseudo-cost has been obtained. If SW2 is equal to one, the node with the best functional value is chosen. If SW2 is equal to two (the standard strategy), the node with the best estimation is chosen. If only one of the successor nodes had been created then that would be the next branching node. If no candidate waiting node has been obtained, the choice is controlled by switch SW3. If SW3 is equal to zero, then the last created waiting node is chosen if, as yet, an integer solution has not been obtained. If at least one integer solution has been obtained, the candidate waiting node with the best estimation is chosen. If SW3 is set to one, the last created waiting node is chosen. If SW3 is set to two (the standard strategy), the candidate waiting node with the best estimation is chosen.

Total reliance on node estimations is wrought with problems. Some of the estimations may be misleading, projecting a very good solution value, but which turns out to be infeasible. Also, it is just that part of the tree where the choice of the variable is most important that estimations are least reliable. Choosing the branching variable on the basis of misleading estimations can lead to an almost arbitrary tree search.

Search Stopping and Restricted Resumption

MIP offers facilities for studying a problem in several successive runs, each time resuming the search from specified waiting nodes. More precisely, MIP offers all required facilities to stop the search provisionally and save the tree when specified conditions are satisfied. These conditions might be when, say, a specified execution time has elapsed, or say, when a specified number of nodes is obtained, or say, when a specified number of nodes is obtained, or say, when a specified number of integer solutions is obtained. MIP also allows the search to resume after certain presently waiting nodes have been disabled to prevent generation of their descendants during this new part of the search. Moreover, a variable which has so far been considered continuous can be declared integer, and vice-versa.

Ending the Search and Proven Optimality

The optimality of the best integer solution obtained thus far is proven by definition when it is certain that no better integer solutions can be expected from the current waiting nodes (i.e. the functional value of the best current waiting node is worse than the functional value of the best integer solution so far). The search is over when the candidate set is empty, that is, when there are no more waiting nodes or all waiting nodes are postponed. Thus, the criterion used in MIP for proving optimality of an integer solution is a function of the dropping rule used in the search. The search procedure, however, can be over before, when, or after optimality is proved, depending on the candidature rules in effect.

Summary of the Chapter

All algorithms have their limitations. In spite of sophisticated exclusion rules, enumeration methods such as branch-and-bound still remain combinatorial. And being basically combinatorial, larger problems (and there are many large ones of considerable practical importance) can easily overwhelm generalized algorithms. There are many parameters that be set to aid or guide problem solution. Heuristic decision rules and problem formulations and even direct analyst intervention can be used to limit the tree search. Experimentation with a scaled down version of the model can pay great dividends in understanding the model, solution strategy and cost (Forrest, Hirst and Tomlin, 1974). Attempting to formulate, generate and then solve a large and complex model immediately without prior experience can be extremely costly, if not impossible.

Large scale integer programming has, however, become a viable economic proposition. It is true that many of the most effective methods are heuristic in nature and there is substantial value of user information and intervention. In this respect the state of the art of large scale integer programming is reminiscent of large scale linear programming of years ago. The final test of the values of the present algorithms is their ability to produce answers which satisfy the user and which are obtained at reasonable expense in both time and money.

The most important criteria in deciding on a solution strategy seem to be (1) getting a "good" integer solution quickly, and (2) quickly gaining confidence that the current solution is in fact optimal or so near optimal as to be practically indistinguishable, given the accuracy of the data. Getting a good integer solution quickly is important for two reasons. One, it provides early in the tree search a drop level that will preclude the development of some of the unpromising tree branches. Secondly, in the case the search is interrupted and not resumed, at least one good integer solution is provided. Knowledge of the exact optimum solution to an integer programming problem is often in practice either impossible (due to excessive computing time or storage requirements) or no more attractive than the more easily computed near-optimal solution. The incremental cost of a precise solution may not be justifiable given real world data and uncertainty. Obtaining in a reasonable time, several near-optimal solutions may well satisfy the needs of the practitioner in the field. However, some confidence that a much better integer solution is not just on the verge of discovery by the algorithm when the search is terminated is required.

While it would be ideal to have a system which solved every problem efficiently and completely automatically the presence of complexities and special features makes such a "black box" approach uneconomic for most models. For this reason it is usually best to run large and complex problems as a series of moderate length runs enabling inspection of the progress so far (Forrest, Hirst, and Tomlin, 1974). In a sense, LP computations are coming full circle. In the early days, LP routines usually required the analyst to be present at the machine to make on-the-spot decisions. This practice came to be regarded as both a burden to the analyst and an intolerably inefficient use of computers. For more than two decades, techniques have been developed to automate the computational runs. Now, however, as the power of computers, program systems, and algorithms has come to fruition, it appears necessary for the analyst to play a greater role once again in directing the execution of preprogrammed procedures.

Determining the most efficient solution strategy for a particular model is a difficult task. There are many parameters that can be set in various combinations to aid or guide the problem solution. Various heuristic programming techniques can also be used to provide additional information (e.g. rounding the continuous solution to provide a drop level from the beginning of the search). Additions to the problem formulation and priority lists of the integer variables (e.g. requiring subsets of the integer variables to sum to an integer fairly high in the priority list) can help, too. Even human intervention during the course of the search can with experience help shorten the solution process (Geoffrion, 1976).

Mixed integer programming is highly model and structure dependent. Large scale exploratory efforts to solve large scale problems (i.e. repeated solving of the same model with different solution strategies and heuristics) is not only expensive, but the results are model specific. Efficient strategies or parameter settings on small models may not be the most efficient for large ones (Gauthier and Ribiere, 1977).

There is also the problem of using a well-documented, efficient, and sufficiently sophisticated mathematical programming system of wide availability, problem capacity, and ease of use. While the solution algorithms are the usual focal point of selecting a mathematical programming system, the other components of the system (e.g. solution output, control programming, input requirements, ability to interface with other routines, etc.) are also important. It is in this area that MPSX-MIP is especially well-designed (Slate and Spielberg, 1978).

CHAPTER IV

AN OPTIMUM MACHINERY COMPLEMENT SELECTION SYSTEM (OMCSS)

Introduction

On the surface, formal computerized analytical techniques appear highly desirable for assisting farmers with their farm planning problems. At first glance, it would appear that these procedures, when combined with a computer, provide an extremely fast, efficient and systematic means of analyzing farm management and investment problems. To a degree this hypothesis is true, but the practical use of these techniques for large scale assistance to farmers involves much more than the availability of computer time, a model, and suitable solution algorithms.

The advent of the computer promised many things for farm management and agricultural economists promised still greater things in the name of the holy black box. Electronic record systems were developed and rushed to the field. Linear programming was employed to the delight of researchers filled with visions of "bench mark and representative farms" becoming household words. Theories on what could and should be done by joining the farmer and the computer provided the text for many worthy journal articles. Alas the glow of the dawn turned into another sunset with the farm manager still using shoe box record keeping and rule of thumb managing (Kletke and Brant, 1974).

There are several possible reasons for the lack of continued success in getting management tools and techniques recognized and adopted by farmers.

Problems with Extension Software Systems

Previous attempts to use the computer for practical farm advice have generally had to be accompanied by vast investments of professional research labor, not only in the program development and model-building stages, but well into the routine application stage. This continual need for research support is one explanation for the failure of many extension applications of research tools. In many cases, the continued support has had to come from the system developer himself since most computer programs are usually delicately handcrafted with many subtitles and other pitfalls for the inexperienced or unwary. When the project originator or programmer moved on to other projects, the system floundered.

Too many previous efforts have also required extensive training by the farm managers before the tools or techniques could be used. Exposure to unfamiliar concepts presented in unfamiliar terms, using unfamiliar techniques and tools, working with unfamiliar data all aimed at some future undefined dividend does not hold the attention of many pressed by the need for current decision-making.

There is a continuing problem of coordination and interface between the model development end of projects (done by researchers) and the application end (done by extension workers). The researcher is rewarded for building models, publishing them and their one-shot applications and pushing on to other research projects on the frontier of the research profession. The extension worker is, however, left many times with a maze of undocumented procedures, unlabeled output, incomprehensible input forms and computer programs which "bomb" at every data change, even though most models are developed with extension application as the primary source of public benefit. It is no wonder that few models are carried further than the thesis library shelf. The models may be good and useful, but their packaging and the developer's lack of attention to mass production requirements render them useless.

In the absence of appropriate extension software, research labor has generally been called upon to determine the structure of the problem to be analyzed, collect or verify the necessary data, develop and debug the computer programs and explain the results to user groups. There are, however, few economies of scale in this sort of work as additional farm problems are analyzed. Average and marginal costs are likely to be similar and can be measured in hundreds of dollars (at least in public cost) per application or much more.

Similar average and marginal costs are not a serious problem in research since many research projects are relatively unique one-shot affairs. Researchers are also much more concerned with effects of changing the structure of the problem (in the least, building new models from old ones) but not the data, than in holding the structure the same and applying new data, as do extension workers. The researcher therefore develops a program that is flexible as possible so that the structure of his model can be easily changed from one application to the next. In contrast, the extension worker wants a computer model that has a fixed structure so that he can change the data on successive runs, without altering the interpretation of the results obtained.

Desired Characteristics of a Computer Program for Extension Application

To adequately solve extension problems, computer programs (software) must have the characteristics of clarity, speed, and reliability. Even though these characteristics are laudable virtues at any time, they deserve particular emphasis in developing extension computer software.

Clarity

The information that the farmer or extension worker is required to supply and the results given back to him must be easily understood. The input data requirements of the program needs to be expressed in terms familiar to the user. Farmers can supply data in their terms much more readily than if unfamiliar ratios (e.g. hours per acre versus acres per hour) are used even if it is the unfamiliar form that is ultimately used by the computer. Secondly and perhaps more important, farmers have some instinct for what is reasonable if a coefficient is expressed in familiar terms. Without this "protection" numerous data errors can be made--garbage being the ultimate result.

The need to accept data in terms most meaningful to farmers necessitates some kind of data generator or translator program which converts the data provided into the form required by the model and solution technique. The computer can, however, do much more to ease the user's data input problems.

Speed

It is obviously desirable that there be a minimum delay between problem contact and the availability of a suggested solution. If the delay exceeds a week, it is doubtful whether a program can be considered really suitable for use in extension. Delays occur primarily in clerical and mechanical procedures used to prepare the data for processing. And, if a report writer is not available, written interpretation of the results can be very time-consuming. For all practical purpose, given a large modern computer system, computer execution time is not a significant obstacle to timely processing.

Here again, powerful data generators and report writers can help. Sophisticated, but simple to use, data generators can reduce the volume of input required by accessing stored data sets, by providing default values (the user only inputs the desired changes), by simplifying programming procedures (one inputted command generates the desired set of commands), and by automatically checking for unreasonable data values, missing data or commands (hopefully eliminating the need for re-processing due to input error and oversight). By reducing the keypunching required, the complexity of the data to be punched, and the expertise needed to run the program, significant decreases in turn-around time can be made.

Reliability

Related to the requirement of speed is that of reliability. Unreliable software is both slow and high cost. It is slow because nonsense ouput must be reprocessed; it is high cost for the same reason, plus the need for a large amount of professional time to diagnose the problem and make corrections. Attainment of program reliability can be assisted by limiting changes to the source program, having reliable clerical help, verifying punched cards, and programmed checks and diagnostics. Providing and maintaining good system documentation is a must, so if problems do occur, (every sophisticated computer program has undetected "bugs") they can be resolved quickly.

The extension worker operates under an altogether more demanding set of rules when it comes to program reliability than does the researcher or model-developer. If due to some input error or even some programming error a "funny" answer is produced, the researcher can because of his knowledge of computers, in general, the inner workings of the program, in particular, and the solution algorithm, understand and explain how the funny answer was obtained. The extension worker is in a quite different position. He may not have any deep understanding of how the computer arrives at its answer; he may not even have detailed knowledge of the data used by the client; and his first intimation that something is amiss may be when his client draws it to his attention. If this were not enough, he likely has to strive for some of what could have gone wrong while his client is interrupting any semblance of thought processes by saying "Well?" at irregular intervals (Candler, Boehlje, and Saathoff, 1970).

Efficiency

It is possible and desirable to substitute capital, in the form of appropriate computer software, for research and extension labor. There is also no appreciable difference between running a highly sophisticated and complex computer program (with respect to its inner workings) and one which bulldozes its way to a solution (one black box looks like most any other). There may be, however, substantial economies which might be realized. A sophisticated control program in MPSX might be "canned" and still allow through interfacing techniques a considerable number of options remaining open for the user. Various checks normally applied to manually generated data may not be needed to data generated by a fully-debugged generator. However, even though results and matrices will be both generated and analyzed by computer, it would be undesirable to dispense entirely with the "BCDOUT"-type listing, the "PICTURE"-type display, or with the eight character mnemonic names for variables. Nonoptional, suppression of the system logging might also be ill-advised. Some of the reasons are: (a) it is useful to be able to remove most of the errors from a matrix generator by simply listing the matrix; (b) it is useful for the analyst to be able to understand the raw output from the MPS, to do the output analysis by hand when it is not worth writing on output analyzer, or to answer supplementary questions about the solution not covered by the ouput analyzer; (c) it may be convenient to make special additions or revisions to the problem using the standard MPS revise facilities, with or without going through matrix generation.

Farmer Adoption of Computerized Decision Aids

For farm management tools to be adopted, farmers must have confidence in the results of their efforts. Confidence in any program or system is greatly enhanced if the user trusts the personnel involved. The user gains additional confidence by the control he exercises over the data. Farmers must feel that they understand what the system requires in the way of data. Further, they must feel the information they provide is correct and complete. Farmers understand all too well the concept of 'garbage in, garbage out'. And finally, confidence in the computer output depends mostly on obtaining a reasonable answer and understanding the relationships that brought about the computer answer.

The OSU Farm Management System

A possible contradiction to the long history of frustration in farm management education and the adoption of computerized decision tools is the Farm Management System at Oklahoma State University. Evidence is accumulating that the approach used is continually gaining more acceptance by Oklahoma farm managers. There has been considerable interest in the system and its component programs nationally as well.

The OSU system is a series of interrelated or compatible components. Each component can be utilized as a separate tool in making farm management decisions or tied in with various other components. The separable but compatible feature enables users to work directly on a particular farm management problem without requiring numerous preliminary steps. Yet, the farm manager is constantly reminded that each decision should be part of an overall plan involving concepts handled by the other components.

One of the major components of the OSU Farm Management System is the budget generator. The budget generator is a computer program designed to do all the computations associated with budget building. As part of the budget generator system, various input and output data handling and data storage procedures have been developed. One of the data banks contains machinery complement cost and performance data.

By accessing the machinery complement data banks of the budget generator, the OMCSS continues the "separate but compatible" concept. It also reduces the need for maintaining an updating duplicate sets of machinery complement data.

The OMCSS Software Package

The OMCSS is directed toward providing non-professionals a sophisticated computerized tool to aid them in their machinery selection and management problems. The system is designed not only to prepare the users problem for solution, solve it, and report back the results; but to do so efficiently, in terms of both computer execution time and total processing effort. Every attempt has been made to make the system easy for non-professional personnel to manage and run.

To simplify execution procedures, the OMCSS combines into a single job step programs and algorithms for generation of the machinery selection model, solution of the model via the MPSX-MIP mathematical programming system, and suitable display of the results. By integrating these separate functions into a single programming system, the user need not know the intimacies of MPSX, FORTRAN, or a separate matrix generator command language. But, by having these programs available, the user also would not be required to know how to represent his problem in algebraic terms, or how to reformulate the mathematical model for easier solution, or how to convert the reformulated model into a format for solution by a mathematical programming system (MPS), or how to program the MPS to handle the problem and solve it in an appropriate manner, or finally how to interpret the results.

Normally, a matrix generator program will have one or more card input files (OSU's LP-FARM has two), MPSX generally has two card input files (one for the control program and one for inputting the matrix), and a report writer program, one or none. Keeping all of these various data card files separate and in proper order could be a difficult task. However, with a single integrated programming system there is only one card input file and with only a few exceptions, commands and data can be placed in any specified order. Programming instructions and data are passed to the appropriate programming via special interfacing procedures or common storage devices.

Program Flow of OMCSS

The program flow of the OMCSS can be logically separated into four basic segments--problem formulation, model specification, model solution, and report of the results. The first segment must be prepared manually, while the latter three are accomplished automatically by the computer under the command of the OMCSS control program.

Problem Formulation

Problem formulation is the combining of a conceptual model with the practical needs of the user. If a computer model can satisfy directly the user's needs or the user can conceptualize his needs in to the problematic terms of the model, or both, then the next step is the preparation of a command program for the computer. The command program communicates the user's problem, the desired analyses, and particular processing procedures to the computer.

Figure 14 provides a flowchart of this procedures for the OMCSS. The decision point is there to underline the fact that every model is inappropriate. Different models are just inappropriate for different problems. A good computer system will also minimize the work and grief involved in these necessarily manual processes of problem formulation and preparation of the command control program.

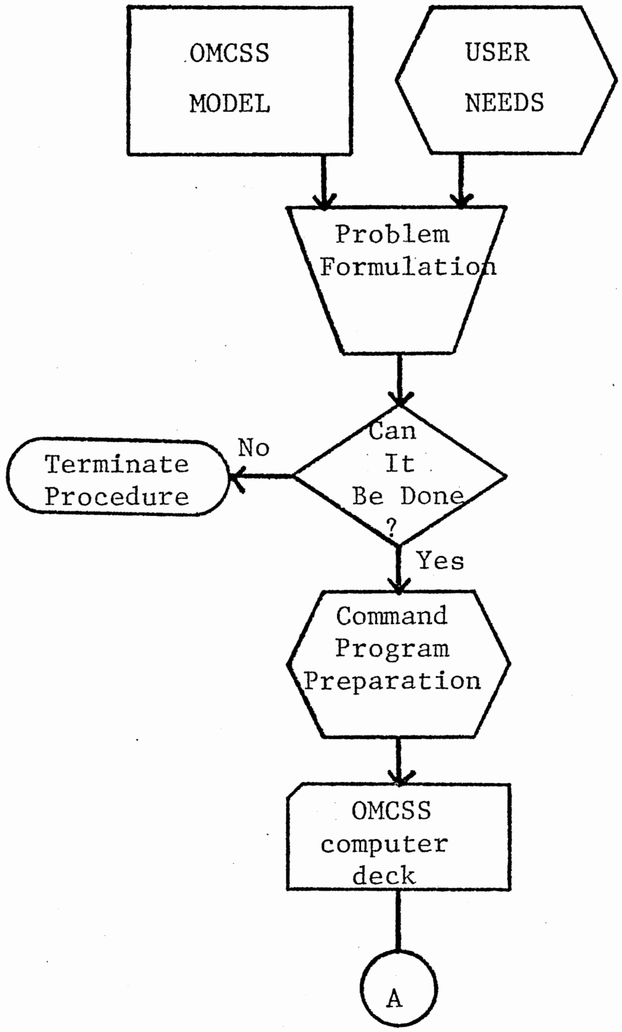

Figure 14. Flowchart for OMCSS Procedures

Model Specification

The next segment - model specification - is the first computerized part of the system. In fact, though it generally accomplishes many more functions than its name, the computer program which actually does the work of this segment is known as the matrix generator. A flowchart of the basic functions, program and data flows of the OMCSS matrix generator is shown in Figure 15.

The control program and data deck prepared by the first segment is inputted to the matrix generator. This data is then used by the matrix generator to draw data from the OSU or FEDS Budget Generator machinery complement data banks in what could be treated as a data collection process. Once all the data requirements are satisfied, certain data processing and computations are performed to complete the data requirements of the OMCSS model. From these computations, some additional machinery cost analysis and output can be prepared at the option of the user. Certain other displays, like the full machinery complement from which machinery alternatives are drawn, can also be prepared. The last primary function is the actual generation of the model for input into the mathematical programming system (MPSX).

As a programmer's note, the matrix generator, itself programmed in the FORTRAN language, is actually executed within an IBM MPSX-MIP "canned" control program. Commands read by the matrix generator are passed to the user that MPSX is a subprogram of OMCSS (the matrix generator and control program), in fact, MPSX is the main program and the matrix generator and control program is the subprogram.

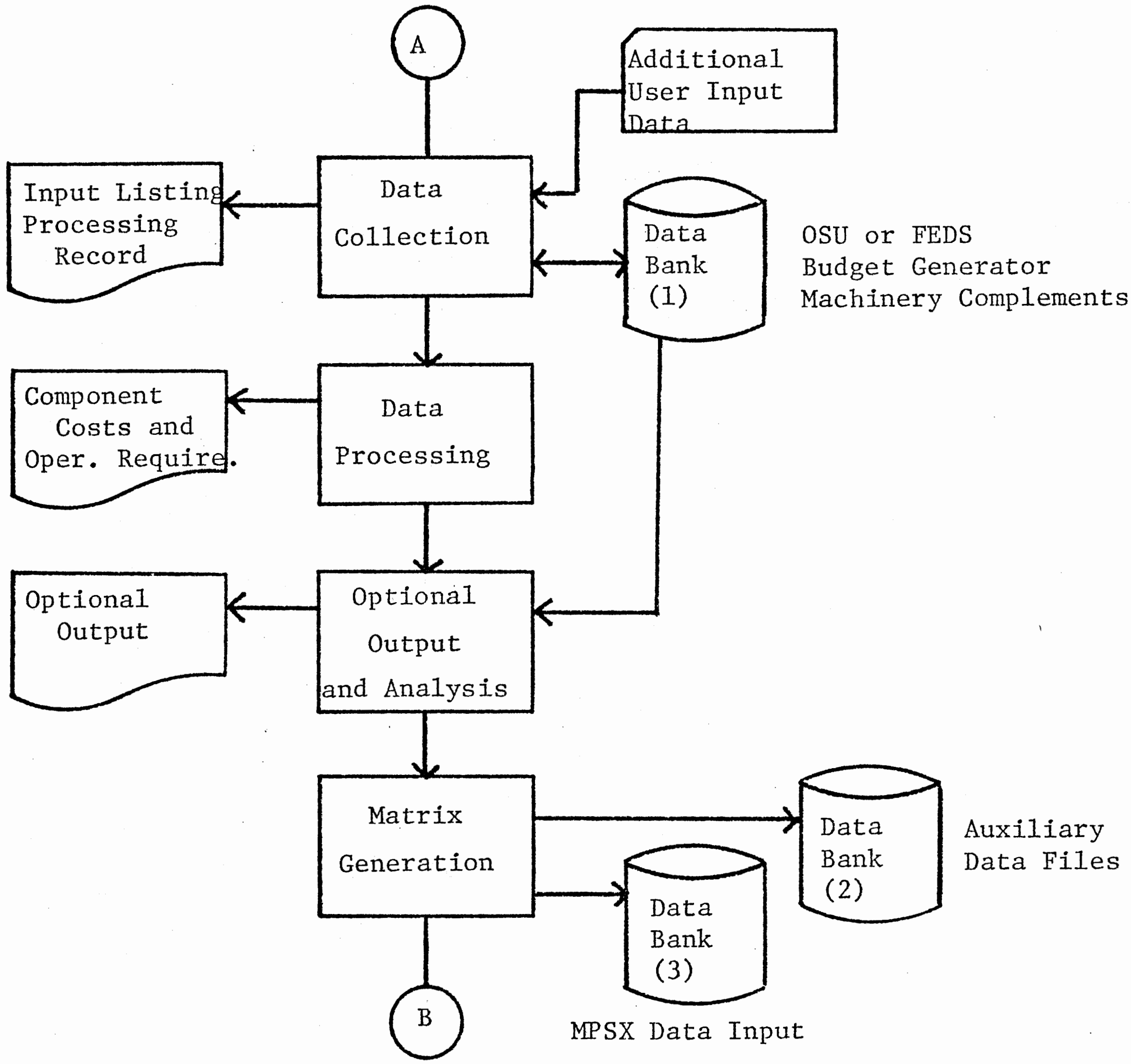

Figure 15. Program and Data Flows for OMCSS Matrix Generator

Model Solution

The solution of the model in OMCSS is primarily a sophisticated, but straight forward application of the facilities of IBM's MPSX-MIP. As shown in Figure 16, program control passes from the matrix generator program to MPSX where the input data generated by the matrix generator is read and converted (along with any optional external matrix revisions) into MPSX's internal representation. The MPSX "problem" is set up and the solution procedure entered. As previously discussed, MPSX solves the continuous version of the model and then utilizing a branch-and-bound algorithm searches for the optimal integer solution. Periodically, the problem bases and search trees are "saved" on the PROBFILE for subsequent resumption of the search and analysis. As solutions are determined, they are stored for analysis by the report writer.

Report Writing

Report writing in mathematical programming terms refers to the processing of solutions from LP or MIP runs for presentation in a convenient format. Operations, in general, consist of searching for data vectors in a filed solution, grouping them, summing or adjusting their activity levels, and constructing tables from them with appropriate titles, column headings, and row names. In many cases, it is also a matter of reattaching various additional detailed information stripped off during the problem formulation stage, including the decoding of the various coded names.

In OMCSS, the report writer accesses the MPSX solution, the machinery complement data bank, and the auxiliary filed of the matrix generator to

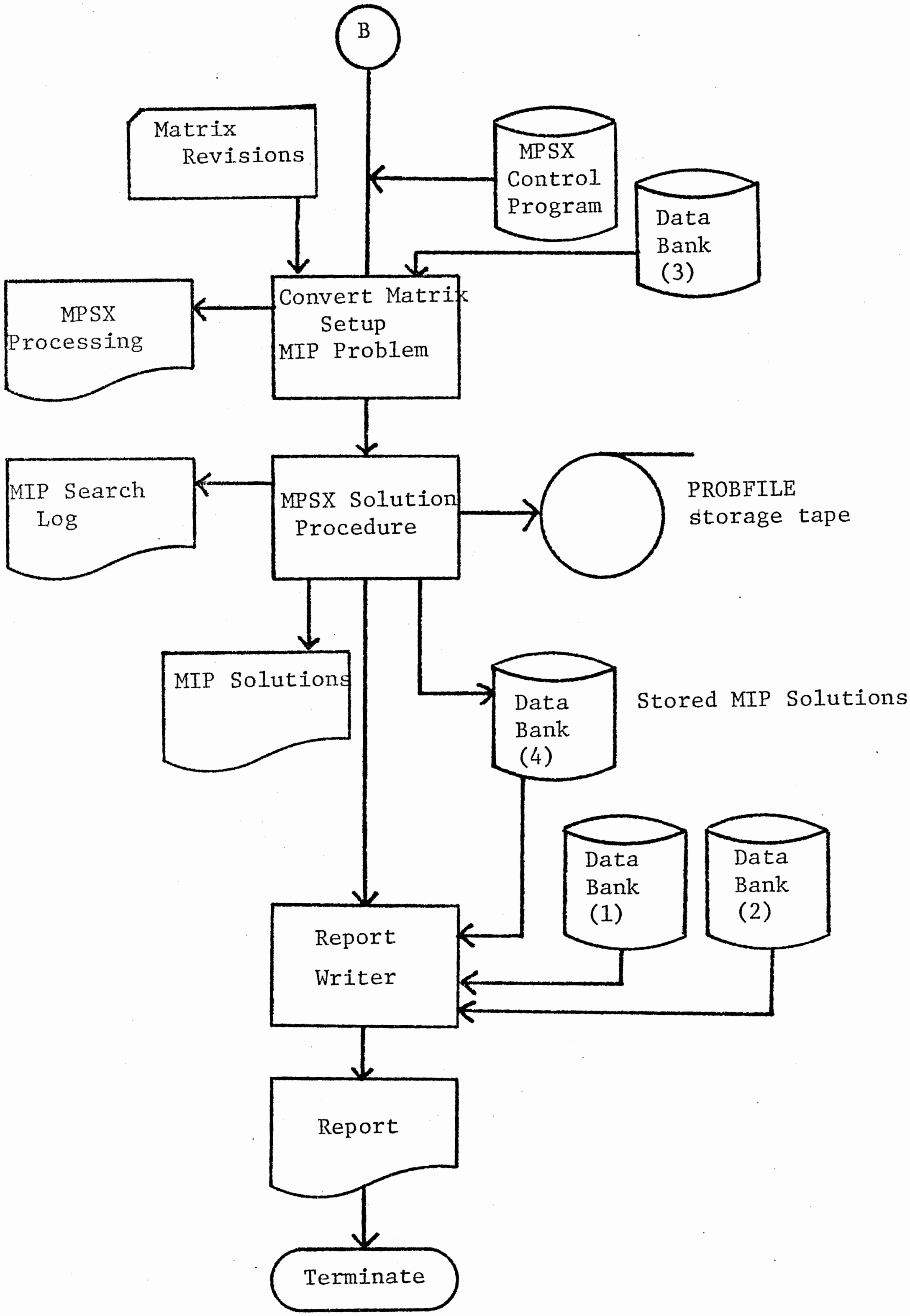

Figure 16. Complete Model Flowchart, OMCSS

formulate a readable and convenient report. While shown in Figure 16 as the final step before termination, the report writer may, in fact, be executed several times during the course of an OMCSS job (e.g. a report may be produced for every feasible integer solution).

Additional Programming Features

The OMCSS has a number of features to aid in processing and improve flexibility. One feature is that the program may be executed in one continuous run, as previously described, or in a series of runs, where one or more segments or options within a segment are executed in a single run. In particular, the options for stopping or resuming the integer search procedure are well developed. Various programming schemes and procedures are available to "save" any computational process made on the progress made on the problem in case of equipment failure, or running out of computer time, or numerous other possible causes for a "busted" run. Other features provided include procedures for "rounding up" continuous solutions, keeping clock times on various procedures, allowing multiple runs, and performing parametric analysis on integer solutions.

The OMCSS Output

The OMCSS output consists of several parts. First is a simple listing of the input data and commands. Next is a processing record of the program as it processes each item or data section of the input deck. It is here that important data checks, default assumptions, and diagnostic helps are displayed. The third major part of the output is a display of the machinery alternative and their calculated capacities and costs, the operational requirements, and other resources available (e.g. hours available per time period, wage rates, etc.). Also, in this section of output, are many other optional print-outs and tables, displaying, for example, the machinery complements from which machinery alternatives are drawn. The fourth major part of the output consists of the processing record of the MPSX-MIP procedures as they attempt to solve the model. This part of the output is primarily used for diagnostic purposes and is directed toward the professional advising of farm managers. There are several options which can expand or contract the volume of material produced. And lastly, the report writer section of the output provides the user the solution or solutions to the model defined in terminology and a format easily interpreted.

Processing an OMCSS Job

Processing the data for OMCSS consists of coding, keypunching, submittal for computer execution and examination of the output. Most of the coding is procedurally handled by use of an input form. Keypunching requires no knowledge of the OMCSS system or the farmer's situation. Keypunchers that are not acquainted with the OMCSS input forms can be adequately instructed within 15-30 minutes of time. Most OMCSS runs would require less than 50 computer cards to be keypunched, many of which could be mass produced and then inserted as called for by the input form. A listing of the data input used to run the 1500 acre case problem is displayed in Figure 17.

Summary of the Chapter

In this chapter, the OMCSS was presented as a complete computer software package for extension's use in providing farm manager's a sophisticated computerized tool to aid them in their machinery selection

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NONRNP  080711
PERIOD
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     0  16.4 64.26
     0   7.9   7.9     0  62.9  62.9  62.9     0
  62.9     0  62.9
  23.1     0   1.9  28.1  62.9   .94     0   .94
     0     0     0
     0     0     0  16.4     0     0     0  1.88
     0     0     0
     0     0     4     0     0     0     0   .94
  62.9     0     0
     0     0     0     0  26.2  28.1     0     0
     0     0  26.2
     0     0     0  27.6     0     0     0     0
     0     0     0
   120 106.5110.25101.25 112.5   190   185 130.5
123.75 124.5 112.5
$ENDSEC$
RANK
M.B.PLOW101020101021101022101023101024101025101026
CHISEL        101061101062101063101064101065101066
T.DISK        101011101012101013101014101015101016
SPRGTTH 101071101072101073101074101075101076101077
DRILL   101031101032101033
ROW.CULT101041101042101043
ROW.PLTR101051101052101053
TRACTOR 101001101002101003101004101005101006101007
$ENDSEC$
XOLDNAMEF1500AC
XRHS    SL1500
PARAXRHSINCR15AC  100.    1000.
FARMSIZE 15.
INTGPROCOPTIMIX
CONTPROCPRIMAL
COSTMASK11
MXOUTPUT
NORANGE
GENERATE
STORPROB
EXECUTE
STOP
```

Figure 17. Input Listing for the OMCSS 1500 Acre Case Problem Run

and management problem. The problems and needs of Extension software systems were discussed. The program flow of the system was also presented and explained. Though not a User's Guide, many of the various features and options programmed into the system were revealed.

CHAPTER V

APPLICATION OF THE OPTIMUM MACHINERY COMPLEMENT SELECTION SYSTEM

Application Objective

A secondary objective of this study was to identify the optimum farm machinery complements for a set of southwestern Oklahoma farms of varying cropland acreages. The potential economies of scale involved with farm machinery technology can thereby be identified for the area and farms of similar resources and enterprise mix.

The existance of economics of scale in farm machinery use is well-known, but their magnitude and the extent to which moderately sized farms are able to benefit (and ultimately pass on these benefits to consumers) are not well known. If these economies can be quantified, then policy makers and society in general can decide whether the economies associated with large farms (of which economies in machinery use is a major component) are great enough to merit sacrifices in other directions (e.g. decline of the rural population and commerce, and concentration of the means of production). If small farms are to be encouraged and economically protected, the magnitude of the competitive forces pushing toward greater size must be known.

Farming in Southwestern Oklahoma

Southwestern Oklahoma agriculture is quite diversified in the variety of crops which are grown in the area, especially in relation to other parts of the country (Figure 18). Winter crops, such as (HRW) wheat and barley, summer crops, such as cotton, peanuts and sorghums, and perennials such as alfalfa are all prevalent. The machinery requirements for these crops are equally diverse in both the timing of the operations (e.g. primary tillage can occur during the summer (for wheat) and during the fall or early spring (for cotton and sorghum) and the operations applied (e.g. both row-planted and drilled crops are represented). However, the only problem in applying the OMCSS to this type of research is one of fulfilling the data requirements of the OMCSS model.

The Data Requirements

The Average Farm Enterprise Mix

There has always been considerable difficulty in identifying an "average" farm for study. Statistical averages distort the enterprise specialization found among individual farms of a given size. Representative or "typical" farm organizations generally change composition as their farm size increases. Measurement of the economies of scale from a representative set of farms of varying size may be biased since some of the economies may be derived from changes in enterprise mix. Since we are concerned here with technical economies of scale embodied only in machinery technology and use, a fixed proportion, "average" farm organization and enterprise mix will be used.

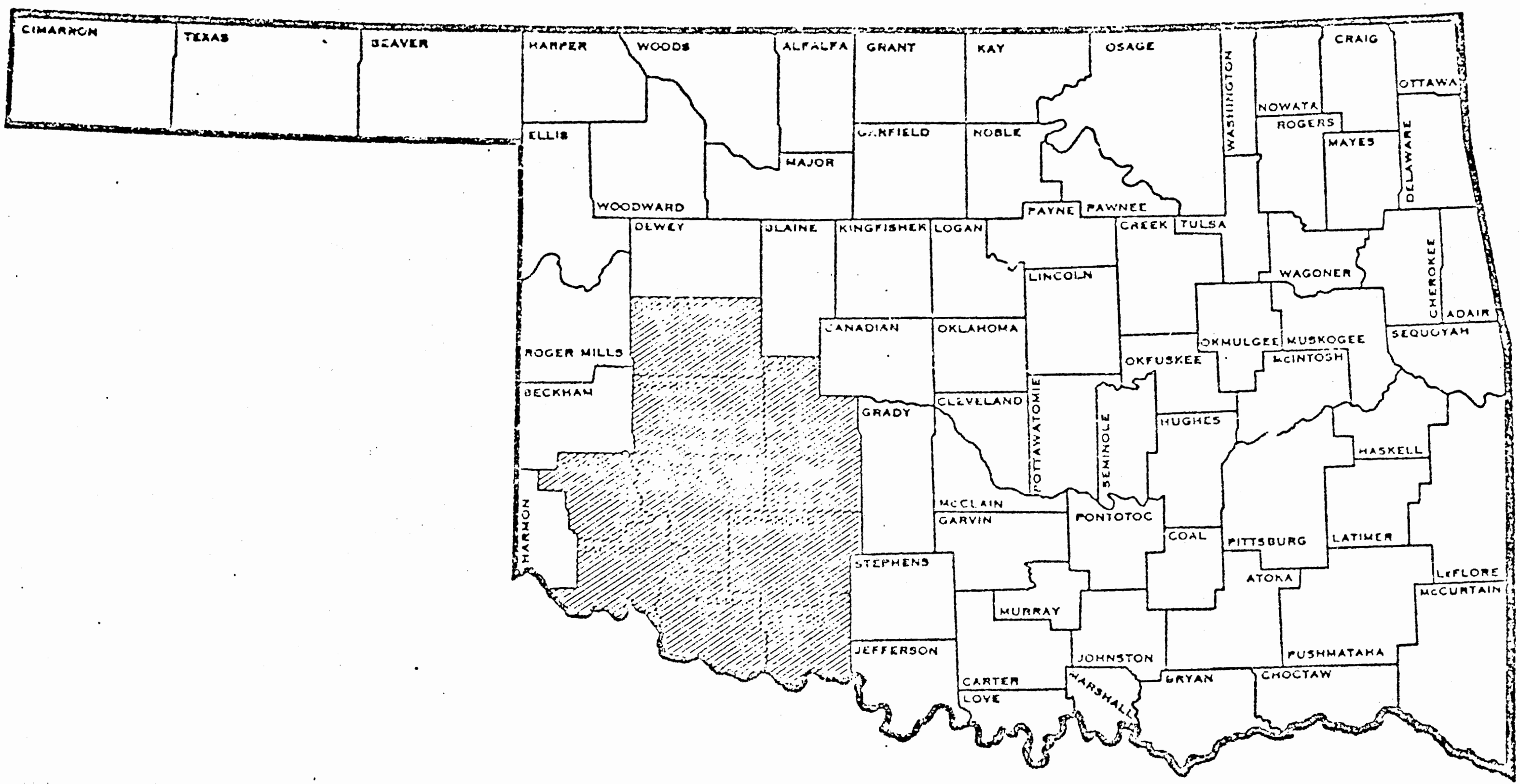


Figure 18. Southwest Oklahoma Analysis Region

During the period 1973 through 1975 planted acreages of various crops as a proportion of the total acres planted in southwestern Oklahoma were relatively constant. A rather simple, yet realistic, farm enterprise mix was developed from these data. Table 6 summarizes this sample enterprise mix. The establishment of the enterprise levels as percentages (or acres per hundred acres of farm size), makes it possible to easily enlarge the farm size and maintain the same farm organization regardless of the total number of acres operated by the farm unit.

Machinery Operation Requirements

With the crop enterprise mix given, the machinery operation requirements for the farm unit can be easily compiled from available (Oklahoma State Extension Service) crop budgets (Provence, 1975). The total machinery requirements for a given size of farm is calculated by multiplying the number of acres of each crop by the crop's operational requirement for a particular machinery operation during a particular time period for all crops, machinery operations, and time periods. The combined machinery requirements per 100 acres of cropland in the case farm is shown in Table 7, by farming practice and time period.

The time periods in Table 7 are numbered one through ten and represent one month of the calendar year (consecutively beginning in January and excluding March and November). Time period eleven is redundant in that it represents an alternative operational requirements for time period five (June).

As an example, all seven crops in the farm enterprise mix require tandem disking as a machinery requirement. Beginning in January, cotton (16.4 percent) and grain sorghum (6.7 percent) crop ground are disked in

Table 6. The Crop Enterprise Mix for an "Average" Southwestern Oklahoma Farm, 1973-75

Crop or Other Land Use Activity	Acres per Hundred Acres of Cropland
Wheat	59.4
Cotton	16.4
Grain Sorghum	6.7
Alfalfa	4.7
Sudan	4.0
Barley	3.5
Peanuts	1.9
Farmed Cropland	96.6
Waterways, fencerows, lanes, etc.	3.4
Total	100.0

Table 7. Operational requirements for the southwest Oklahoma farm, hours available, and other parameters by time period (acres per 100 acres of farm size)

Farming Practices		Time Per. (1)	Time Per. (2)	Time Per. (3)	Time Per. (4)	Time Per. (5)	Time Per. (6)	Time Per. (7)	Time Per. (8)	Time Per. (9)	Time Per. (10)	Time Per. (11)
Moldboard Plow	(Acres)*			2		1					16	64
Chisel	(Acres)		8	8		63	63	63		63		63
Tandum Disk	(Acres)	23		2	28	63	1		1			
Springtooth	(Acres)				16				2			
Drill	(Acres)			4					1	63		
Row-Cultivator	(Acres)					26	28					26
Row-Planter	(Acres)				28							
Tractor	(Hours)	120	107	110	101	113	190	185	131	124	125	113
Wage Rate ($/Hr.)		2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
Avail. Free Labor (Hr)		0	0	0	0	0	0	0	0	0	0	0
Avail. Hired Labor(Hr)		1200	1065	1103	1-13	1125	1900	1850	1305	1238	1245	1125

*Rounded to the nearest acre

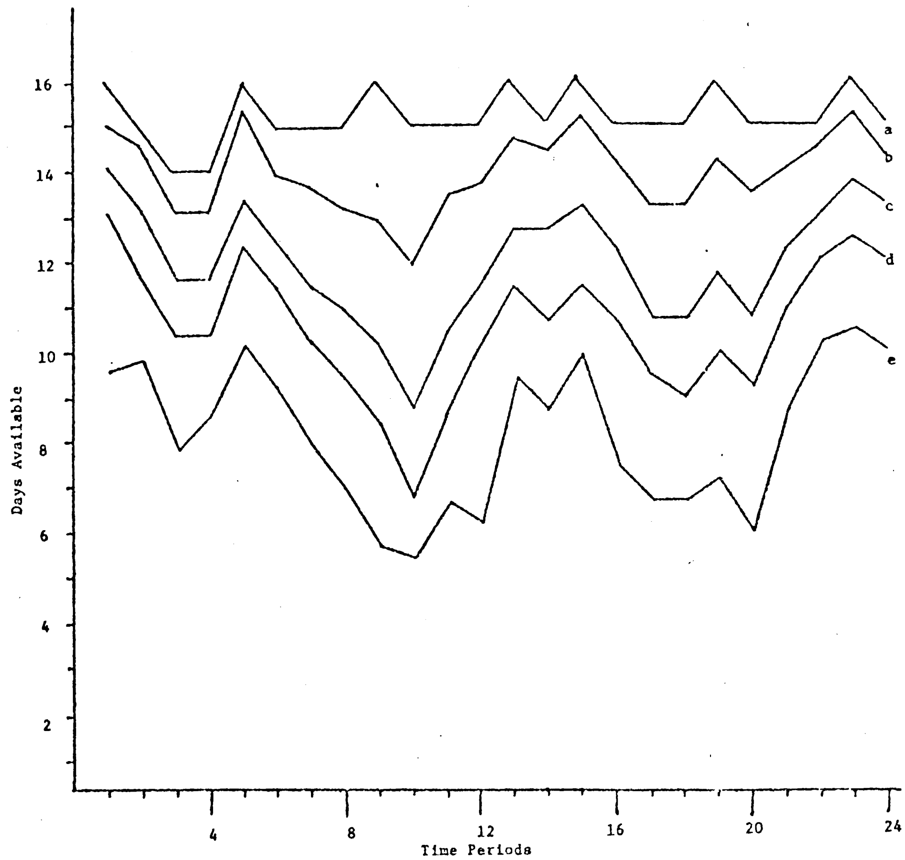
preparation for planting in the approaching spring. In April, the peanut ground (1.9 percent) is disked, followed by two more diskings in May. Also, in May, the cotton and grain sorghum ground is disked again. In June, the barley and wheat fields (62.9 percent) are disked (after harvest). In some years, however, the barley and wheat acres are to be moldboard plowed rather than disked. For this reason, time period eleven is defined to require the complement to have this capacity.

The timeliness cost functions for all operations are assumed to the square-corner U-shaped in which the time length of the base of the U is equal to the hours available in the time period.

Time Available for Fieldwork

The estimated days available for fieldwork within each time period to accomplish the required machinery operations were prepared from tables developed by Reinschmiedt (1973) for southwestern Oklahoma. Reinschmiedt determined from a survey of producers the amounts of field time lost as a result of alternative amounts of rainfall, given soil type and soil moisture conditions prior to the rain. In southwestern Oklahoma, rain and wet field conditions are the primary impediments to fieldwork.

There is a tradeoff between the specified number of (suitable) days available during a specific time period and the percentage of time (in the long run) one could expect to have at least the specified number of days occur (i.e. the timeliness risk level, or simply the timeliness level) (Figure 19). For this analysis a 97.5 percent timeliness level was chosen, indicating a relatively high preference for "always" being able to accomplish scheduled tasks in the time periods provided. The number of days available for each time period is displayed in Table 8.



a. Maximum number of days available in each time period.
b. Distribution of days available at the 50 percent level of timeliness.
c. Distribution of days available at the 60 percent level of timeliness.
d. Distribution of days available at the 90 percent level of timeliness.
e. Distribution of days available at the 98 percent level of timeliness.

Figure 19. Distribution of Days Available at Varying Percentage Levels of Timeliness for Sandy Loam-Loam Soil Types.

Source: Reinschmiedt, 1973.

Table 8. Days Available, Hours Worked per Day Available, and Total Hours Available By Time Periods.

Month	Time Period	Days Suitable Available (97.5% Timeliness)	Hours Available for Machinery Operations per Day	Total Hours Available
January	1	20.00	6	120.0
February	2	17.75	6	106.5
March	-	-	-	-
April	3	15.75	7	110.25
May	4	11.25	9	101.25
June	5,11	13.25	10	132.5
July	6	19.00	10	190.0
August	7	18.50	10	185.0
September	8	14.50	9	130.5
October	9	13.75	9	123.75
November	-	-	-	-
December	10	20.75	6	124.5

The number of hours (per operator) during an available day for machinery operations can vary considerable from time period to time period. The hours available for machinery work can vary due to season (e.g. due to changes in the amount of daylight), working conditions, other seasonal demands for time, and operator preference. A conservative timeliness level can be offset with a "liberal" allocation of hours per day to machinery operations, and vice-versa. The hours available for machinery labor per day available are also displayed by time period in Table 8.

The total hours available per operator by time period is the product of the days available and hours available per day (Table 8).

Machinery Alternatives

Farm machinery complements must accomplish the required functions within the constraints imposed by crop maturity, weather variability, labor availability and climate. Machinery manufacturers and their dealers provide farmers an almost unlimited assortment of machinery types, brands and sizes. Added to this is the almost unlimited combination of circumstance embodied in a farm's existing machinery complement.

For purposes of this study, it is assumed that there is no existing set of machinery either to trade-in or blend into an optimum set. Since the crop production plan is also assumed to be repeatable year after year with certainty in terms of technical coefficients and prices, the complement selected will be stable over time (i.e. the different wear-out lives of the various components of the complement will have no real effect).

While a farmer might mix and match among full-line and short-line manufactures, one full-line brand was chosen for purposes of data continuity. The idea being that list pricing practices with respect to machinery capacity would have less "market" distortion within a manufacturer's line than among a set combining several long or short line manufacturers.

The set of machinery alternatives must meet several requirements for the model. First, at least one machine implement must be defined for each operational requirement in the case problem (since custom-hire is not defined). Secondly, the machinery implements must be "ranked" relative to the tractor alternatives such that a tractor of a given rank has sufficient power to "pull" an implement of the given rank or lesser rank. Obviously, a tractor alternative must be defined with sufficient rank (power) to pull the largest (rank) implement.

For the case problem, seven sizes of moldboard plow (three 14 inch bottoms to eleven 16 inch bottoms), six sizes of chisel plow (10 foot to 29 foot), six sizes of tandem disk (approximately 10 foot to 27 foot), seven sizes of springtooth harrow (12 foot to 60 foot), three sizes of grain drill (approximately 13 foot to 40 foot), three sizes of row planter and cultivator (2 row to 8 row), and seven sizes of tractor (35 PTO horsepower to 175 PTO horsepower) are defined for a total of 42 machinery alternatives. The machinery alternatives are ranked into seven relative size categories as displayed in Table 9.

Machinery cost and performance are calculated with the basic formulas presented in Chapter II. Assumed values for speed, draft, field efficiency, repair cost, use and ownership, remaining farm value factors and other basic parameters and factors are displayed in Tables 10 and 11.

The calculated annual ownership cost, operating cost per hour and field capacity in acres per hour is presented in Table 12. Particularly

Table 9. Machinery Complement Alternatives and Relative Size Rank

Machine or Implement Type	Draft per foot of width[a] (PTO hp)	Relative Size Ranking 1	2	3	4	5	6	7
Moldboard plow[b]	9.8	3-14" (34.4)	4-14" (45.9)	5-16" (65.6)	6'18" (88.6)	7'18" (103.3)	(2)5-16" (131.2)	5,6-16" (144.3)
Chisel plow[c]	6.0	n.a.	10' (64)	14' (84)	16' (96)	20' (120)	24' (144)	29' (174)
Tandem Disk[c]	5.8	n.a.	10'1" (58.08)	14'3" (82.08)	17'1" (98.4)	19'11" (114.7)	24'2" (139.2)	27'1" (156.0)
Springtooth[c]	3.0	12' (35.6)	18' (53.4)	28' (83.0)	36' (106.8)	42' (124.7)	54' (160.3)	60' (178.1)
Drill[c]	1.8	13'4" (24)	(2)13'14" (48)	(3)13'4" (72)	n.a.	n.a.	n.a.	n.a.
Row cultivator[d]	1.5	2-row (9.6)	4-row (19.3)	8-row (38.5)	n.a.	n.a.	n.a.	n.a.
Row planter[d]	3.0	2-row (19)	4-row (38)	8-row (76)	n.a.	n.a.	n.a.	n.a.
Tractor[e]	n.a.	35 hp	60 hp	80 hp	100 hp	125 hp	150 hp	175 hp

[a]Defined for a specified speed and field efficiency for each class of implement, where PTO HP/ft = (draft in pounds x speed in mph ÷ 375) x 1.5.

[b]Size given in number of plow bottoms and width of each bottom in inches.

[c]Size given in width of implement in feet and inches.

[d]Size given in number of (38 inch) rows.

[e]Size given in rated PTO horsepower.

Table 10. Assumed Values for Speed, Draft, Field Efficiency, Repair Cost, Use and Ownership, and Remaining Farm Value Factors

Machine	Field Speed	Draft	Field Eff.	Repair Cost Factors RC1	RC2	RC3	Est. Hours of Annual Use	Est. Years of Ownership	Est. Hours of Wearout Life	Remaining Farm Value Factors RFV1	RFV2
	(mph)	(lb/ft)									
Tractors	n.a.	n.a.	n.a.	1.20	.000631	1.6	600	10	12,000	.68	.920
Tandem Disks	4.8	300	.83	.65	.000251	1.8	100	10	2,000	.60	.885
Moldboard Plows	4.1	600	.80	2.00	.002510	1.8	250	10	3,000	.60	.885
Chisel Plows	4.0	375	.80	.65	.000251	1.8	125	10	2,000	.60	.885
Springtooth harrows	5.3	140	.70	.65	.000251	1.8	100	10	2,000	.60	.885
Cultivators	3.8	100	.76	1.00	.000251	1.8	100	10	2,000	.60	.885
Drills	4.5	100	.72	.65	.000251	1.8	100	10	2,000	.60	.885
Planters	5.0	150	.67	.80	.000631	1.6	60	10	1,200	.60	.885

n.a. - not applicable

Source: Provence, 1975

Table 11. Machinery Cost Parameters and Other Factors

Parameter Description	Value
Price per gallon of gasoline	\$0.4390
Price per gallon of L.P. gas	\$0.4390
Price per gallon of diesel	\$0.4390
Interest rate per dollar	\$0.1000
Machinery insurance rate (price/dollar of average investment insured)	\$0.0200
Machinery tax rate (price/dollar of purchase value)	0.0
Price of machinery labor/hr.	\$2.7500
Maximum number of tractors allowed in complement	5.000
Maximum number of tractor-operators allowed in complement	10.000
Factor by which machine hours are multiplied to obtain tractor hours	1.1000
Factor by which tractor hours are multiplied to obtain machinery labor requirements	1.1000
Factor by which the time available is inflated for tractors	1.1000

Table 12. Annual Ownership Cost, Operating Cost per Hour, and Field Capacity

Machine Name and Description[1]	Rank	Field Capacity[2]	Total Variable Cost	Total Ownership Cost
		acres/hour	$/hour	$/year
Moldboard plow 3-14 (SI)	1	1.4	$0.83	$204.27
Moldboard plow 4-14 (SI)	2	1.9	1.32	326.84
Moldboard plow 5-16 (SI)	3	2.7	1.99	490.26
Moldboard plow 6-18 (SI)	4	3.6	2.32	571.96
Moldboard plow 7-18 (SI)	5	4.2	2.65	653.67
Moldboard plow (2)5-16 (D)	6	5.3	3.58	882.46
Moldboard plow 5,6-16 (D)	7	5.8	3.91	964.17
Chisel plow 10' (R)	2	3.9	$0.23	$163.42
Chisel plow 14' (R)	3	5.4	0.30	212.44
Chisel plow 16' (R)	4	6.2	0.35	245.13
Chisel plow 20' (F)	5	7.8	0.70	490.26
Chisel plow 24' (F)	6	9.3	0.82	571.96
Chisel plow 29' (F)	7	11.2	0.94	653.67
Tandem disk 10'1" (R)	2	4.9	$0.27	$228.79
Tandem disk 14'3" (R)	3	6.9	0.51	424.89
Tandem disk 17'1" (F)	4	8.3	1.04	866.12
Tandem disk 19'11" (F)	5	9.6	1.08	898.80
Tandem disk 24'2" (F)	6	11.7	1.76	1470.77
Tandem disk 27'1" (F)	7	13.1	1.96	1634.18
Springtooth harrow 12' (R)	1	5.4	$0.10	$ 81.71
Springtooth harrow 18' (F)	2	8.1	0.14	114.39
Springtooth harrow 28' (F)	3	12.6	0.33	277.81
Springtooth harrow 36' (F)	4	16.2	0.47	392.20
Springtooth harrow 42' (F)	5	18.9	0.58	490.26
Springtooth harrow 54' (F)	6	24.3	0.82	686.36
Springtooth harrow 60' (F)	7	27.0	0.94	784.41
Grain drill 13'4"	1	5.2	$0.78	$653.67
Grain drill (2) 13'4"	2	10.4	1.72	1438.08
Grain drill (3) 13'4"	3	15.7	2.55	2124.44
Row cultivator 2-row	1	2.3	$0.27	$147.08
Row cultivator 4-row	2	4.7	0.30	163.42
Row cultivator 8-row	3	9.3	0.36	196.10
Row planter 2-row	1	2.7	$0.69	$245.13
Row planter 4-row	2	5.4	0.83	294.15
Row planter 8-row	3	10.8	1.25	441.23
Tractor JD830 35 HP	1	n.a.	$1.26	$1021.58
Tractor JD2030 60 HP	2	n.a.	2.09	1571.66
Tractor JD4030 80 HP	3	n.a.	2.83	2200.32
Tractor JD4230 100 HP	4	n.a.	3.64	2986.15
Tractor JD4430 125 HP	5	n.a.	4.36	3300.48
Tractor JD4630 150 HP	6	n.a.	5.21	3929.15
Tractor JD6030 175 HP	7	n.a.	6.14	4714.97

[1](SI) semi integral, (D) drawn, (R) rigid, (F) flexible or folding design.

[2]n.a. - not applicable.

interesting is the average annual ownership cost when calculated on a dollars per unit of size (width in feet for implements and PTO horsepower for tractors). A quick look verifies that these figures are hardly constant or smoothly increasing or decreasing in many cases. Thus, simplified cost functions for machinery (i.e., rather than using actual list prices, one uses a simple mathematical function exhibiting constant, increasing or decreasing cost economies) could be very misleading. This data, computed from prices provided by a local machinery dealership (Kelley Farm Equipment Company, 1975), exhibits numerous irregularities. For instance, tractor ownership costs per PTO horsepower are virtually constant at between \$26 and \$27, but bumpy with an average of \$29.19 at the 35 horsepower size, \$26.19 at the 60 horsepower size and \$29.86 at the 100 horsepower size. Other data show increasing per unit prices up to 100 horsepower and then decreasing per unit prices (Edwards, 1979). Kletke and Griffin (1975) cite continuous economies of scale in list prices. Obviously, any optimum complement would be sensitive to the relative costs of machinery capacity of various sizes. The importance of defining farmer-available equipment at farmer-available prices is therefore paramount.

One could justify a number of shapes for the cost per unit of size curve for various implements. As implements are manufactured wider, the weight and draft of the implement increases rapidly, requiring stronger members and braces. Also, as width increases, the need for flexibility and the capacity to fold-up into more convenient travel widths is greater and require more expensive designs. There can thus be several forces affecting implement prices based on cost of manufacturing. First since only one set of wheels, height adjustment, and base frame are needed some economies might be had as the basic design is either narrowed or widened with relatively inexpensive attachments. At some point, however, a larger, heavier, and more costly base design is required. And finally, as width increases further, another even heavier design with perhaps one or more fold-up wings (hydraulically assisted) would be required. Therefore, an increasing step function exhibiting decreasing average costs within each step might be possible. Depending upon the particular type of implement each "step" would accommodate one or more sizes of the implement.

Alternatively, an implement might show fairly flat or decreasing average costs throughout. This type of cost function might be expected for highly unitized implements, especially where draft is not a major problem, like row planters and cultivators. Decreasing average costs result from a relatively high lump-sum cost of a set of major components (e.g. a tool bar for implements or a cab and hydraulic system on tractors).

Generation of the Models

The OMCSS was used to generate and solve the machinery complement selection model for each representative farm size. The selection model was same size for each farm situation (i.e. no machinery alternatives were dropped for the smaller farms), though some of the elements within the model changed in magnitude according to the farm size. The models generated contained 391 rows (260 inequality constraints, 86 equality constraints, and 45 "free" (for accounting purposes) constraints and 472 columns (429 unbounded activities and 43 bounded activities (42 of which were integer). The 391 by 472 matrix contained 3668 non-zero elements for a matrix density of 1.08 percent. Each model was generated in approximately 0.2 minutes of computer time.

Solving the Models

With 42 integer variables defined and a conventional LP problem in excess of 250 rows, the case problems were not easy or quick to solve. The standard MPSX-MIP strategy was used to solve all models. Extensive problem reformulations was not experimented with due to funding limitations, though adding some "common sense" constraints reduced computer costs by 20 percent. Providing "drop levels" calculated from rounded-up continuous solutions did not significantly reduce the tree search. Neither did solving first for a partial integer solution (e.g. integerizing only the tractor activities) significantly increase solution efficiency. Direct human intervention in the solution procedure was not attempted for lack of helpful solution experience in solving this class of MIP problem.

Solution times for a proven optimum integer solution were highly variable. All were long and expensive computer jobs; some were just longer and more expensive than others. Generally, a fairly good integer solution (within 10 percent of the optimum) would be found fairly quickly. Additional integer solutions would be found sporadically during the search. Finally a long (an additional 2 or 3 times the current elapsed time from the last integer solution) stretch of computation would be done to "prove" the optimality of the last integer solution found. How long to wait (at $10 or $20 per minute) for proven optimality or a better solution was the most difficult question to answer during the computer runs. It is always somewhat distressing to watch the computer bill go up faster than the objective function comes down.

For example, in solving the 1500 acre case problem, a continuous optimal solution with a functional value of $22,745 was found in 23 seconds (Table 13). The first integer solution with a functional value of $25,914 was found 2.4 minutes into the MIP search. A second integer solution was found 1.5 minutes later. At 10.62 minutes into the search, a third integer solution was found with a functional value of $24,717. By this time, the best possible integer solution which <u>might</u> be found would have a functional value no less than $23,029. A fourth integer solution was found just under six minutes later. Integer solutions five and six came back-to-back at almost 19 minutes into the search. Continuing the integer search almost 40 more minutes produced no new integer solutions, an only slight increase in the best possible solution value (proven optimality is when the best possible value equals or exceeds the functional value of the lost integer solution), and an increase in the number of awaiting nodes. Based on the lengthy computation without a better integer solution being found and results of the other farm sizes (i.e., the sixth solution was in line with suspected economies of scale) the search was not resumed and optimality proven.

Results of the Model Runs

In order to map out the envelope curve, six farm sizes (100 acres, 320 acres, 1000 acres, 1500 acres, and 2000 acres) were modeled and solved. In the process of solving for optimum machinery complements, several feasible (but not optimal at the particular farm size) machinery complements were produced as well. Summaries of the results obtained are given in the following sections.

Table 13. Summary of the Solution Procedure for the 1500 Acre Case Problem

Integer Solution	Integer Functional Value	Best Possible Solution	Node Number	Iterations Since Start of Search	Branches Abandoned	Number of Awaiting Nodes	Elapsed CPU Time (Min.)
Continuous	$22,745	--	0	--	--	--	--
1	25,914	$22,974	61	439	5	28	2.40
2	25,212	22,974	103	700	9	39	3.90
3	24,717	23,029	232	1942	26	83	10.62
4	24,497	23,029	348	3047	48	109	16.50
5	24,315	23,055	393	3430	66	100	18.70
6	24,297	23,055	398	3455	70	83	18.91
-		23,244	1111[a]	10269	n.a.	118	58.00[b]

[a]Number of nodes reached at time of job termination.

[b]Elapsed time of search at time of job termination.

The 100 acre case farm

The 100 acre farm situation was the smallest farm organization considered. Farms smaller than 100 acres would probably either use small-scale equipment (i.e., garden tractor, other motorized non-riding equipment, etc.), use custom operators, or not have the enterprise mix assumed. A 100 acre farm was expected to use the smallest equipment available. A detailed cost and hourly use summary of the optimum complement is presented in Table 14.

Since there was neither a chisel nor a tandem disk defined compatible with the 35 PTO horsepower tractor, the 60 PTO horsepower tractor, the minimum feasible size to accomplish all tasks, was selected. Except for the selection of the 4-row cultivator, all other implements selected were the minimum size available. Total implement usage was 145.5 hours. Total tractor usage was 160.0 hours and labor usage was 176.0 hours (1.76 hours per acre). Total annual average cost of the optimum 100 acre complement was $4185.30 or $41.85 per acre.

The optimum 100 acre complement also contains significant excess capacity. In fact, up to 175 acres could be farmed feasibly before timeliness considerations impose major constraints.

The 320 acre case farm

The 320 acre optimum farm machinery complement is presented in Table 15. It differs only slightly from the 100 acre complement. An additional 60 horsepower tractor and replacement of the moldboard plow and row planter with the next available size sums up the changes. The extra tractor and higher capacity equipment is primarily required for time periods 5 and 11 (June). Total average annual machinery cost is

Table 14. Detailed Cost and Hourly Use Schedule for the 100 Acre Southwestern Oklahoma Case Farm.

Machine		1	2	3	4	5	6	7	8	9	10	Total
		Time Period (hours)										
M.B. Plow	3-14"			1.4		1.0					11.8	14.1
Chisel	10'		2.0	2.0		16.2	16.2	16.2		16.2		69.0
T. Disk	10'1"	4.7		.4	5.8	12.9	.2		.2			24.2
Spring-tooth	12'				3.0				.3			3.4
Drill	13'4"			.8					.2	12.0		13.0
Cultivator	4-row					5.6	6.0					11.6
Planter	2-row				10.2							10.2
Tractor	60hp	5.2	2.2	5.0	20.9	39.3	24.7	17.8	.8	31.0	13.0	160.0
Machinery Labor Used		5.7	2.5	5.5	23.0	43.2	27.1	19.6	.9	34.2	14.3	176.0

Annual Average Fixed Costs	$3312.06
Annual Average Operating Costs	$ 389.25
Annual Average Labor Costs	$ 483.98
Annual Average Machinery Costs	$4185.30 ($41.85 per acre)
Total Hours of Labor	176.0 hours
Excess Capacity	75.0 percent
Maximum Capacity	175.0 acres ($27.66 per acre)

Table 15. Detailed Cost and Hourly Use Schedule for the 320 Acre Southwesten Oklahoma Case Farm.

Machine Type(no.)	Machine Size	Time Period 1	2	3	4	5	6	7	8	9	10	Total[a]
						(hours)						
M.B. Plow	4-14"			3.3		2.3					28.3	33.9
Chisel	10'		6.5	6.5		51.9	59.9	51.9		51.9		220.6
Tandem Disk	10'1"	15.2		1.2	18.5	18.5	.6		.6			77.5
Spring-tooth	12'				9.7	9.7			1.1			10.4
Drill	13'4"			2.4					.6	38.4		41.5
Cultiva-tor	4-row					18.0	19.3					37.2
Planter	4-row				16.3							16.3
(2) Tractor	60 hp	16.7	7.2	14.8	49.0	124.9	79.0	57.1	2.5	99.4	33.1	481.6

Annual Average Fixed Costs	$5055.31	
Annual Average Variable Costs	$2637.53	
Annual Average Machine Costs	$7692.84	($24.07 per acre)
Total Hours of Labor	529.76 hours	
Excess Capacity	1.51 percent	
Maximum Capacity	324.8 acres	($23.80 per acre)

[a]Totals do not include time period 11.

$7692.84 or $24.07 per acre. The complement requires 529.8 hours of labor (1.66 hours per acre) and contains only 1.51 percent of excess capacity. At maximum feasible acreage (324.8 acres), the average cost per acre falls to $23.80 per acre. Obviously substantial economies of scale exist between the 100 acre complement ($41.85 per acre at 100 acres) and the 320 acre complement.

The 500 acre case farm

The optimum complement for the 500 acre case farm contains multiple implements as well as multiple tractors (Table 16). In comparison to the 320 acre complement, the single 4-(14 inch) bottom moldboard plow was replaced by two plows, a 3-14 inch and 5-16 inch bottom plow. The chisel and tandem disk implements were similarly upgraded to rank 3 size. The springtooth size selected was also increased one step (to 18 feet) as well as the row cultivator (to 8-row). Total labor used by the complement is 604.5 hours per year or 1.21 hours per acre.

The total average annual cost of the complement is $10,483.21 or $20.97 per acre. The most constraining or complement setting time period is number 11 (June) with its relatively heavy plowing and chiseling requirements. Had these requirements embodied in time period 11 not been given, the model would probably not have selected the second plow.

The 1000 acre case farm

Four tractors were selected in the optimum complement for the 1000 acre case farm. Total average annual cost was $17,789 or $17.79 per acre. Labor usage totaled 898.7 hours (.9 hours per acre) and excess capacity was 3.02 percent.

Table 16. Detailed Cost and Hourly Use Schedule for 500 Acre Southwest Oklahoma Farm

Machine Type (no.)	Machine Size	Time Period 1	2	3	4	5	6	7	8	9	10	11	Total[a]
						(hours)							
M.B. Plow	3-14"											16.6	0.0
	5-16"			3.6		2.6					30.9	112.5	37.1
Chisel	14'		7.3	7.3		57.9	57.9	57.9		57.9		57.9	246.2
T. Disk	14'3"	16.8		1.4	20.4	45.7	.7		.7				85.7
Spring-tooth	18'				10.1				1.2				11.3
Drill	13'4"			3.8					.9	60.1			64.8
Cultiva-tor	8-row					14.0	15.1					14.0	29.1
Planter	4-row				25.5								25.5
(2) Tractor	80hp	18.5	8.0	17.6	61.6	132.2	81.0	63.7	3.0	129.8	34.0	221.2	549.6
Machinery Labor Used		20.3	8.8	19.4	67.8	145.5	89.1	70.1	3.3	142.8	37.4	-	604.5

Annual Ownership Cost	$ 6990.82	
Annual Operating Cost	$ 1830.01	
Annual Labor Cost	$ 1662.38	
Total Cost	$10483.21	($20.97 per composite acre)

[a]Totals do not include time period 11.

The 1500 acre case farm

The optimum complement for the 1500 acre case farm continued the pattern set by the previous optimum complements for the smaller case farms. The pattern being selection of increasingly higher powered tractors, full sized primary tillage (chisel and moldboard plow) equipment, and multiple tractor size and implement size configurations. In the 1500 acre solution, a single large tractor (150 horsepower) entered the complement for primary tillage requirements. Other requirements were for the most part accomplished by smaller (80 horsepower or less) tractors and equipment.

Total average annual cost of the complement was $24,297 or $16.20 per acre. Annual labor usage totalled 1243 hours or .83 hours per acre.

In Table 17, the progression of machinery complements from the continuous solution to the best integer solution found (optimality in this case was not proven) during the search. In this case problem, note that merely rounding the continuous solution would not be an accurate predictor of the final integer solution. There is also not a regular pattern in the adjustments to the complements displayed (other complements were, of course, implicitedly constructed during the course of the search procedure). Thus, the next integer solution cannot be predicted by a progression of integer solution already determined by the procedure (i.e., the procedure is not visibly heading toward another integer solution as evidenced by solutions already found).

The 2000 acre case farm

The 2000 acre farm situation was the largest sized farm analyzed in the study (see Table 18). The 2000 acre optimum machinery complement

Table 17. Continuous and Integer Solution Complements for the 1500 Acre Case Farm

Machine Name and Description	Continuous Solution Complement	Integer Solution Complements 1	2	3	4	5	6
		- number of machines -					
Moldboard plow 3-14 (SI)	3.36	4	2	3	3	3	3
Moldboard plow 4-14 (SI)	.						
Moldboard plow 5-16 (SI)	.	1					
Moldboard plow 7-18 (SI)	.42						
Moldboard plow (2)5-16 (D)	.40	1		1	1	1	1
Moldboard plow 5,6-16 (D)	.		1				
Chisel plow 10' (R)	.			1	1	1	1
Chisel plow 14' (R)	.61		2				
Chisel plow 16' (R)	.						
Chisel plow 20' (F)	.						
Chisel plow 24' (F)	.35			1	1	1	1
Chisel plow 29' (F)	.45	1	1				
Tandem disk 10'1" (R)	.			2	2	1	1
Tandem disk 14'3" (R)	.61	2	1			1	1
Tandem disk 17'1" (F)	.		1				
Tandem disk 19'11" (F)	.43						
Tandem disk 24'2" (F)	.01						
Tandem disk 27'1" (F)	.						
Springtooth harrow 12' (R)	.90	1	1	1	1	1	
Springtooth harrow 18' (F)							1
Springtooth harrow 28' (F)							
Springtooth harrow 36' (F)							
Springtooth harrow 42' (F)							
Springtooth harrow 54' (F)	.10						
Springtooth harrow 60' (F)							
Grain drill 13'4"	.77	2	2	2			
Grain drill (2) 13'4"	.				1	1	1
Grain drill (3) 13'4"	.23						
Row cultivator 2-row	.63						
Row cultivator 4-row	.						
Row cultivator 8-row	.37	1	1	1	1	1	1
Row planter 2-row	.62						
Row planter 4-row	.						
Row planter 8-row	.38	1	1	1	1	1	1
Tractor JD830 35 HP	3.36	4	2	3	3	3	3
Tractor JD2030 60 HP	.			1	1	1	1
Tractor JD4030 80 HP	.98	1	2	1	1	1	1
Tractor JD4230 100 HP	.						
Tractor JD4430 125 HP	.42						
Tractor JD4630 150 HP	.40			1	1	1	1
Tractor JD6030 175 HP	.45	1	1				

Table 18. Detailed Cost and Hourly Use Schedule for 2000 Acre Southwest Oklahoma Farm

Machine Type	Machine Size	Time Period 1	2	3	4	5	6	7	8	9	10	11	Total[a]
						(hours)							
M.B. Plow	3-14											81.5	0.0
	4-14											57.0	0.0
	7-18											112.5	0.0
	(2)5-16			7.2		5.1					61.9	112.5	74.2
Chisel	29'		14.0	14.0		111.8	I11.8	111.8		111.8		111.8	475.4
T. Disk	10'1"					99.4							99.4
	14'3"	67.1		5.5	81.7	112.5	2.7		2.7				272.3
Spring-tooth	12'				60.8				7.0				67.7
Drill	(2)13'4"			7.6					1.8	120.1			129.6
Cultivator	8-row					56.1	60.2					56.1	116.3
Planter	8-row				51.0								51.0
Tractor	35hp				66.9				7.7			89.6	74.5
	80hp	73.9		14.4	111.4	123.7	69.2		5.0	132.1		123.7	529.8
	125hp				34.5	123.7						123.7	158.3
	150hp			7.9		52.9					68.1	123.7	128.9
	175hp		15.5	15.5		123.0	123.0	123.0		123.0		123.7	522.9
Machinery Labor Used		81.2	17.0	41.6	234.0	465.8	211.5	135.3	13.9	280.7	74.9	--	1555.9

Annual Ownership Cost:	$20698.21
Operating Cost:	$ 7377.76
Labor Cost	$ 4278.73
Total	$32354.70

($16.18 per composite acre)

[a]Totals do not include time period 11.

Another point is that while the complements quickly became multi-tractor, second implements, particularly of the same size, did not appear. Also, the lighter draft finishing operations and planting were accomplished by the smaller power units even when larger power units were available. The use of the big tractors were primarily limited to the extremely high draft operations. The use of the small moldboard plows were a result of the problem formulation involving the "redundant" June period and should perhaps be ignored.

Economies of Scale in Farm Machinery Use

Economies of scale in farm machinery use result from several sources. Foremost, are economies related to spreading the relatively high fixed (ownership) costs associated with machinery use over a greater number of acres. These economies may be reduced however by timeliness factors or the availability of smaller sized machinery at lower total ownership costs. Another source of economies of scale is the labor-saving and therefore cost-saving aspect of operating larger, higher capacity equipment. And finally, there are possible economies of size in purchasing farm machinery per unit of capacity (e.g., the cost per horsepower is likely lower on a high horsepower tractor versus a low one).

Synthetic firm analysis is designed to discover the technical economies of size under static pure competition assumptions. This kind of analysis determines points on a series of short-run average cost (SAC) curves as a basis for sketching the long-run average cost (LAC) curve or envelope curve (Figure 20). Problems of coordinating large sizes of firms are frequently ignored or assumed away. Findings must be interpreted carefully since they show average total cost (ATC) each firm

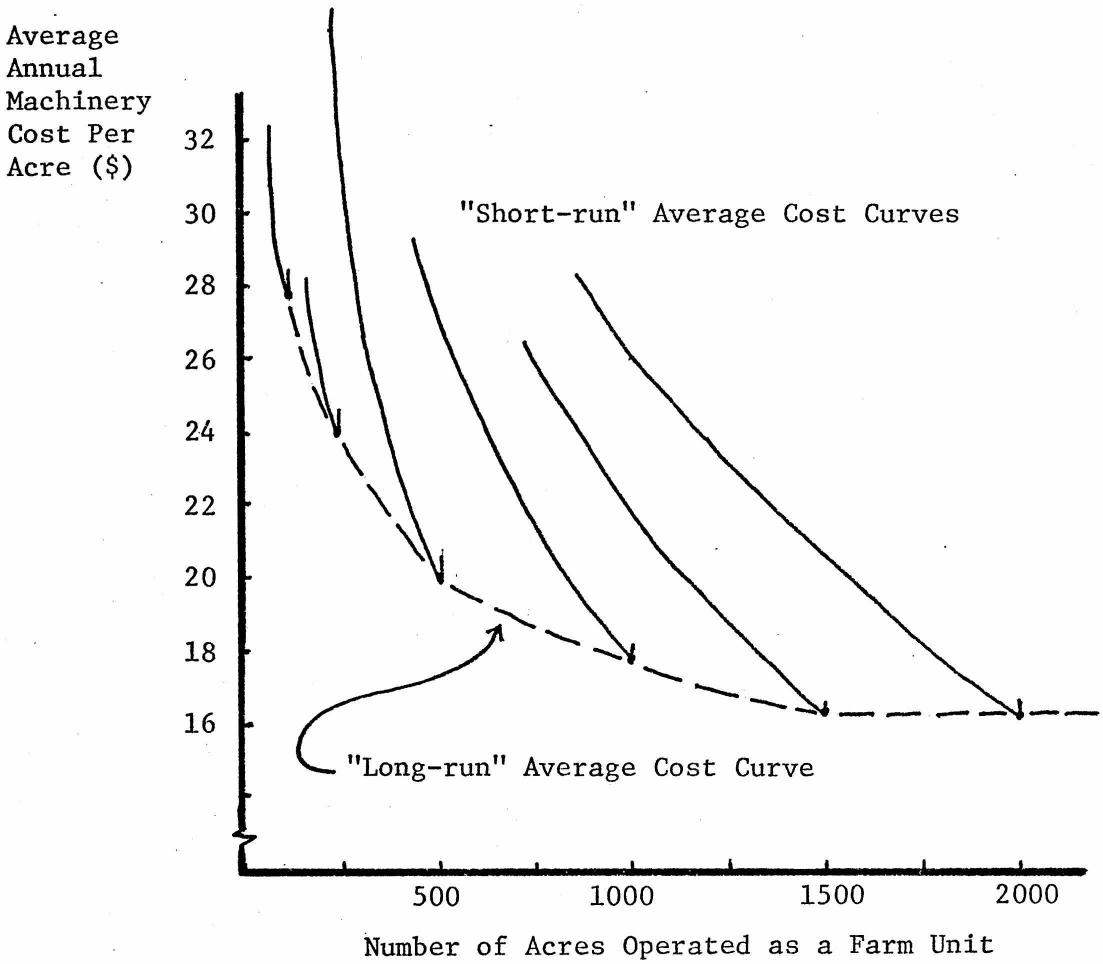


Figure 20. Average Machinery Complement Cost Curves

had a total average annual cost of $32,354.70 or $16.18 per acre. Apparent economies of scale in farm machinery ownership and use were thus virtually constant from the 1500 acre solution to the 2000 acre solution, though the configuration of their machinery complements were quite different.

Labor usage totalled 1555.9 hours per year or .83 hours per acre. Thus no significant labor savings per acre were determined between the 1500 acre farm and the 2000 acre farm.

As in the 1500 acre complement, the larger tractors (150 and 175 horsepower) entered the optimum complement as fairly low (in terms of conventional wisdom) rates of annual usage (128.9 and 522.9 hours, respectively)

Summary of the model runs

The optimum machinery complements determined for each case farm are shown in Table for comparison. For the most part, the differences between complements are as might be expected, with machines in each of the complements growing in size and number as farm size increased. There are, however, a few interesting points which can be seen. For example, the decision model did not select progressively larger tandem disks and springtooth harrows in the fashion it did for chisel plows and moldboard plows. Perhaps, as Bowers (1978) notes, "the more an implement has to be folded, the heavier it gets per unit of width--and naturally the cost goes up." Unfortunately a super-wide springtooth harrow is one of the first implements upgraded to take advantage (or show-off) a new big tractor's power. At least, in terms of cost per unit of width, a harrow is one of the cheapest and most impressive field implements to show off a new big tractor, whether its in an "optimum" complement or not.

Table 19. Optimum Machinery Complements By Size of Farm.

Machine Name and Description	Optimum Machinery Complement by Size of Farm					
	100	320	500	1000	1500	2000
	- number of machines -					
Moldboard plow 3-14 (SI)	1		1		3	1
Moldboard plow 4-14 (SI)		1				1
Moldboard plow 5-16 (SI)			1			
Moldboard plow 6-18 (SI)				1		
Moldboard plow 7-18 (SI)				1		1
Moldboard plow (2)5-16 (D)					1	1
Moldboard plow 5,6-16 (D)						
Chisel plow 10' (R)	1	1				
Chisel plow 14' (R)			1	1		
Chisel plow 16' (R)						
Chisel plow 20' (F)				1		
Chisel plow 24' (F)					1	
Chisel plow 29' (F)						1
Tandem disk 10'1" (R)	1	1			1	1
Tandem disk 14'3" (R)			1	1	1	1
Tandem disk 17'1" (F)						
Tandem disk 19'11" (F)						
Tandem disk 24'2" (F)						
Tandem disk 27'1" (F)						
Springtooth harrow 12' (R)	1	1				1
Springtooth harrow 18' (F)			1	1	1	
Springtooth harrow 28' (F)						
Springtooth harrow 36' (F)						
Springtooth harrow 42' (F)						
Springtooth harrow 54' (F)						
Springtooth harrow 60' (F)						
Grain drill 13'4"	1	1	1			
Grain drill (2) 13'4"				1	1	1
Grain drill (3) 13'4"						
Row cultivator 2-row						
Row cultivator 4-row	1	1				
Row cultivator 8-row			1	1	1	1
Row planter 2-row	1					
Row planter 4-row		1	1			
Row planter 8-row				1	1	1
Tractor JD830 35 HP					3	1
Tractor JD2030 60 HP	1				1	
Tractor JD4030 80 HP		2		1	1	1
Tractor JD4230 100 HP			2	1		
Tractor JD4430 125 HP				1		1
Tractor JD4630 150 HP					1	1
Tractor JD6030 175 HP						1

could achieve if it organized from scratch at one size versus starting from another size. Few large farms start from "scratch." They generally grow from smaller farms.

By fixing the machinery complement at its optimum configuration for each size of case farm and then parameterizing on the operation requirements in fixed proportions per acre of farm size, short-run (since the machinery complement is fixed) average machinery cost curves can be generated. By enclosing the short run average cost curves in an envelope curves the long run machinery cost curve is determined. Only the average cost points of the complements at the specified acreages at which the complements were selected are known to be on the envelope curve. Other points on the SAC may well be inefficient compared to another optimally selected complement.

In Figure 20, the SAC of the optimum complements determined for the various sizes of the case situation are displayed. Substantial cost economies are shown to exist as farm size increases. Total machinery costs per year average more than $26.00 per acre for farms with less than 250 acres in cropland (and similar enterprise mix) compared to near $16.00 per acre for units farming 2000 acres or more. Most of the scale economies are realized however by farms of 750 acres and larger.

The left-hand slope of the SAC's are quite steep inferring that complements with substantial excess capacity are very expensive to own and operate versus complements more closely alined with operational requirements. Optimally selected complements were found to have very little excess capacity (less than 2 percent) indicating that solutions may change significantly with respect to changes in farm size or operational demands. At the same time, however, no optimum complement was found at or beyond its minimum average total cost. Marginal costs were thus significantly below average total costs.

The vertical right-hand side of the ATC curves are related to the squared cornered U-shaped timeliness functions assumed for the operational requirements. Also, there were no real constraints on the number of tractors, number of tractor operators, or hours of labor available for hire which would tend to turn the long-run average cost curve up.

Summary of the Chapter

In this chapter, an application of the optimum farm machinery complement selection system was performed to investigate economies of scale in farm machinery on average southwestern Oklahoma farms. Six sizes of farms were modeled and their optimum complements determined. The short run (machinery complements fixed) average machinery cost curves were developed and a long run "envelope" curve was determined. Substantial economies of scale in farm machinery use were found.

CHAPTER VI

SUMMARY, SUGGESTIONS FOR FURTHER RESEARCH, AND CONCLUSIONS OF THE STUDY

Summary

The management environment faced by farmers today is characterized by uncertainty and change. A farmer can not control the price of his inputs which are provided in the marketplace or the weather which may dominant his day to day decisions. However, in selecting and operating farm machinery, he has wide latitude in the substitution of capital for labor and other variable inputs, and in controlling, in some respect, his relative vulnerability to adverse weather.

The primary objective of this study was to develop a conceptual model, find and apply an appropriate analytical solution procedure, and program a convenient computerized system for determing optimum farm machinery complements. The objective was accomplished by programming an optimum machinery complement selection (computer) system encompassing IBM's MPSX-MIP mathematical programming system. The OMCSS system provides the user with a complete software package with which to input, retreeve, modify and store relevant machinery cost and performance information for immediate retrieval, and access for use as input into the machinery selection model. With the OMCSS, a user can easily formulate a machinery scheduling problem incorporating the subject farm's unique management characteristics, generate the MPSX input matrix, select the desired solution strategy and choose a variety of output summaries and reports.

The optimum machinery complement selection system was used to investigate the potential economies of scale involved with farm machinery use on Southwest Oklahoma farms of average enterprise mix by indentifying their respective optimum farm machinery complements. Substantial economies of schale in farm machinery costs were revealed. Total machinery costs varied from greater than $26.00 per acre for farms with less than 250 acres in cropland to less than $16 00 per acre for units farming over 2000 acres. However, most of the economies of scale were realized by only 750 acres or greater. Optimally selected machinery complements were in some cases performing the operational requirements at 80 percent of the cost of alternative "reasonable" but nonoptimal complements. Few of the optimum machinery exhibited excess capacity greater than 2 percent of the total requirements and were therefore quite sensitive to changes in the given operational requirements. However, the complements selected also represented very well those observed on well-managed commercial farms.

Unfortunately, solution costs were relatively uncertain and high. The computer time required for optimal solution tended to increase exponentially as the number of machine alternatives rose. o a lesser extent, increased flexibility within the decision space lead to greater computer running times. Large-scale programming models can be formulated which are prohibitively costly to solve. However machinery solutions of less than proven optimality can be arrived at much more cheaply. Continued improvement in mixed integer programming solution techniques is needed before widespread application and use of the OMCSS can be expected at the farm extension level.

Suggestions for Further Research

The OMCSS machinery selection model is a practical, understandable and easy-to-use decision aid for advising farmers in their machinery management decisions. It can also be a very valuable research tool. Further research is needed for improving the data on which the model rests improving the formulation of the model itself, improving the algorithnic procedures used to solve the model, and in further applications and extensions of the model.

Further Applications

There are numerous research applications for the model and extensions to it. A few suggestions are listed as follows.

1. Determine optimum whole-farm plans where alternative crop mixes and production systems are selected as well as the machinery complements.

2. Determine optimum machinery complement expansion and contraction paths over the life-cycle of the family farm with particular reference to the changing availability of family labor and the inter-generational transfer of the farm.

3. Investigate the dynamic growth and evaluation of farm machinery complements and expand the enipirical basis of replacement theory with respect to farm machinery.

4. Develop relevant rules-of-thumb (e.g., "buy a size of tractor 5 years before you need it") and test old adages.

5. Determine the effects of changes in interest rates, labor costs, labor availability, risk and timeliness preference, and machinery prices (Kletke and Griffin, 1975).

6. Determine the effects on optimum machinery complements,,the adoption of new production technologies (e.g., min-till, no-till, etc.) or machinery-related environmental policies (e.g., probibition of fall plowing of spring crops).

And this list is far from exhaustive. The machinery and investment problems which could be answered with OMCSS or its extensions are great. It is an area hardly scratched by previous or current researchers.

Model Development

Further research and development could be applied to the OMCSS model itself. Part of the research effort could be applied to facilitating the research applications just mentioned. Other improvements however could be made.

For example, the current model does not allow for multiple uses of implements (e.g., using tandem disks for primary tillage and shallow incorporation of chemicals), variable speed selection, or multiple implement hitches (e.g., tandem disk followed by a harrow). Special exclusion rules are also not easily incorporated into the model (e.g., preventing 4-WD tractors from pulling 2-row cultivators or mixing 4 row equipment and 6-row equipment). In its least-cost mode, OMCSS might be provided some release activity for specific crop requirements at the price (cost) of the expected revenues above average variable costs (i.e., allow the model not to "cultivate" the crop at a loss). Additional labor activities (e.g., purchasing summer help for the summer on an integer basis rather than hourly) might be added to the model. Financial considerations might also be added to the model with the idea that the optimum complement for the low capital farmer might be much different from the high capital farmer.

Data Development

The computer represents the ultimate in mechanization of data production. However, its capacity for the generation of error is at least equal to its capacity for the generation of fact.

model is better than the data fed it. Cost-of-use equations are growing sadly out-of-date. Repair cost estimates, particularly those on larger equipment, are falling badly out of line with available farm record data. Recent research on the performance of large equipment or at today's speeds is sadly lacking. Most of the technical data used in the OMCSS model are extrapolations of equations estimated twenty years ago. Fuel comsumption data for specific tractor models at varying load levels are uncertain. And, of course, timelines cost functions for various operations for various crops are almost nonexistent. Even suitable climatilogical data for the determination of the days available for tillage and fieldwork are not always available and must largely be manufactured.

Reliable data is especially important in integer programming models since there is the possibility of discontinuity of the optimal value as a function of constrant coefficients. A small change in some "soft" coefficient can lead to a sudden incommensurately large change in the optimal solution.

Algorithmic Development

There is a great need for further research in the development of more efficient MIP solution algorithms and in harnessing the full capacity of existing routines. A great deal remains to be learned about utilizing the broad tactical flexibility inherent in LP-based branch-and bound algorithms. There is a wealth of ideas and some computational evidence on the use of various schemes involving various penalties, priorities, branching criteria, "psevdo-costs" and related topics.

There is also a lot of room for improvement in developing improved bounds through improved model presentation practices. Better bounds imply less need for branching, thereby shifting the balance of work to the relatively more efficient machinery of linear programming as opposed to enumeration. To the extent that this leads to the introduction of additional constraints, it reminds one of the most infrequently mentioned suggestion to incorporate cutting-plans into branch-and-bound as a means of improving the tightness of the usual LP relaxation and to facilitate effective bounding.

Since linear programming provides the main computational horsepower for the leading approaches to integer linear programming, especially branch-and-bound, almost any computational advance in LP is automatically beneficial to IP. Generalized upper bounding (GUB), improved representations of the inverse matrix (permitting substantially reduced pivot times and storage requirements) have all proven valuable in IP. This point applies particularly to the field of large-scale LP for the obvious reasons and also because integer programs of moderate size can enlarge impressively when seemingly redundant constraints are added for the purpose of stronger bounds.

There is little doubt that great advances need to be made in reducing the computer time (and related costs) for OMCSS runs. The current computer resources need for modest sized OMCSS problems are large and uncertain. Before the OMCSS can be expected to be successful on a widespread basis, a means must be found to provide cheaper answers for increasingly complex integer problems.

Conclusions of the Study

Commercial farms are larger and more highly capitalized than ever before. Operating margins are and will continue to be slim. The cost of skilled labor will be high. The economic pressures for optimum machinery use will be intense.

Manufactures and their dealers will continue to participate importantly, but informally, in the machinery selection process, just as they do today. We may see, however, farm machinery companies become more deeply involved in developing and employing analytical tools.

Farming has long been considered to be a kind of "art", or even more, "a way of life" somewhat removed from the rigors and pressures of business and economics. Since the beginning of this century, mainly during the last three decades, forces have been underway which have di inished the extent of the "art of farming" and widened the extent of "scientific management". The optimum machinery complement selection system (OMCSS) developed in this study is perhaps a small step in bringing the farmer closer to realizing the benefits of modern scientific management.

This study has to some extent been long on problems and concepts and short on results. A model was formulated, an algorithm harnessed, a computer system devised, and an application made. However, important questions still remain.

How much should be spent by public research institutions for decision aid development and use? At some point, increased information gives decreasing total returns. As models become more ambitious (and this project was more ambitious than originally realized), they require more information from the user (which is an added cost) and may cost more to solve. Some farmers may (and perhaps the public should) rightly decide to have two runs of a small, less demanding, and less precise model rather than one which "simulates the world". Certainly we can overtax our computer facilities (and funding) with mixed integer programming models like OMCSS using currently available solution algorithms and expertise. We are thus reluctantly awaiting a new leap forward in MIP solution technology. In the meantime farmers and researchers have to consider very closely the benefits of any very large MIP problem formulations.

No decision maker wants to be told by his experts what the decision he should make is; he wants to reserve that for himself. What he does desire is to be shown how he himself can utilize to the fullest his knowledge and judgement to determine the decision he wishes to make. Acceptance of the model by the user is the ultimate test of its validity. Hopefully the OMCSS can serve decision makers needs in farm machinery selection and management and will be accepted as another important tool in farm management decision making.

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VITA

Steven Curtis Griffin

Candidate for the Degree of

Master of Science

Thesis: DEVELOPMENT AND APPLICATION OF AN OPTIMUM MACHINERY COMPLEMENT SELECTION SYSTEM

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Neosho, Missouri, March 19, 1952, the eldest son of O. Curtis and Betty J. Griffin.

Education: Graduated from C.E. Donart High School, Stillwater, Oklahoma, in May, 1970; received the Bachelor of Science degree from Oklahoma State University in December, 1973; completed requirements for the Master of Science degree at Oklahoma State University in May, 1980; pursuing a doctoral program of study at Iowa State University in Agricultural Economics, June 1975 to present.

Professional Experience: Employed as a Graduate Research Assistant in the Department of Agricultural Economics, Oklahoma State University, Stillwater, Oklahoma, 1974-1975; Graduate Research Assistant in the Center for Agricultural and Rural Development (CARD), Iowa State University, Ames, Iowa, 1976-1976; and Research Associate in the Center for Agricultural and Rural Development (CARD), Iowa State University, Ames, Iowa, 1976 to present.

Memberships: American Agricultural Economics Association, Southern Agricultural Economics Association, Western Agricultural Economics Association, American Statistical Association.

Honoraries: Phi Kappa Phi, Omicron Delta Kappa, Alpha Zeta.