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*New Methodologies in Agricultural Production Economics: a Review**

1. INTRODUCTION

WRITING a review paper like this one is an exercise in constrained optimization. The objective function is the maximization of the reader's utility, however that may be specified. But the constraints are less clear, so I shall begin by identifying them briefly as they have affected my compilation of this paper. First, in defining 'new', I have taken the year of the last IAAE Conference as a convenient starting point. Thus the coverage of the literature herein spans the somewhat arbitrary period 1970 to the beginning of 1973; the reference list at the end of the paper contains only writings appearing in 1970 or later. In fact, the word 'new' is not particularly appropriate in describing methodological progress; in agricultural economics, as in the pure sciences and the arts, innovation is seldom completely spontaneous. The great majority of 'new' methodology is simply a refinement of tools already in the kit, firmly based in the body of received theory.

Secondly, an important constraint in preparing a review paper is access to material. I do not pretend to have covered the literature exhaustively. In particular, I have not been able adequately to survey writings in languages other than English. Thirdly, I have limited my consideration largely to methodologies whose application or potential application in agricultural economics has already been established. In so far as much methodological work in agricultural economics is stimulated by theoretical developments in operations research, mathematical economics, decision theory and econometrics, one could probably foresee *now* much of the content of a paper written under the above title for the 1976 IAAE Conference, simply by perusing current issues of *Management Science, Operations Research, Econometrica,* and other respositories of 'pure' methodological research.

2. FRAMEWORK FOR ANALYSIS

The study of a problem in the economics of agricultural production must accept, explicitly or otherwise, some model of the firm as the basis

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for analysis [70, 73, 100, 113, 140, 163, 173, 176]. Traditionally, the basic model used has contained a fully rational profit maximizing entrepreneur operating under perfect competition with perfect knowledge in a static environment. The production conditions of the firm have been specified either as the smooth continuous twice-differentiable production function of neoclassical theory, or as the fixed-coefficients production function of mathematical programming. Either way, the decision problems of the firm are seen as constrained extremization problems; under neoclassical theory solution is by means of the calculus, whereas in mathematical programming search methods are appropriate.

As an initial basis for a taxonomy of models, then, a distinction between programming and non-programming models may be used. The former set up the production conditions of the firm as a set of linear constraints, and incorporate a (usually) single-dimensional criterion function. The non-programming models comprise, first, those which may contain the same sort of objective function as the programming models but a smooth-curved production function as the constraint, and secondly, those which broaden the interpretation of the decision problems of the firm to include utility and other subjective considerations. It is convenient to collect together the non-programming models under the heading 'Decision theory models'.

The classification is, of course, not entirely watertight. For example, it is necessary to group simulation models under a separate heading, as they overlap the above boundaries so frequently as to make it a pointless task trying to cram them into one group or another.

There is virtually no assumption in the traditional model of the firm which has not been attacked in some way, and much methodological development consists in efforts to relax one or more of the restrictive assumptions of the basic firm model referred to above. Most interest has centred on modifying the supposition of the decision-maker's complete certainty. It is well known that recognition of risk and uncertainty introduces both stochastic and dynamic elements into decision analysis. These features, then, provide a second criterion for classifying new methodologies, i.e. into those predominantly concerned with stochastic problems, those focusing attention on dynamic aspects, and those containing elements of both. Again, this classification is not perfect but it will serve as a basis for discussion.

The framework of this paper is therefore as follows: First, decision theory models, and secondly, programming models as defined above are discussed. Within each category stochastic and dynamic aspects are distinguished. Thirdly, simulation models are considered. In the final section an appraisal of possible future methodological developments is made.

3. DECISION THEORY MODELS

3.1. *Static deterministic models*

Decisions as to the levels of variable inputs which the rational manager should employ are soluble by response surface methods when relationships between outputs and inputs can be adequately described by smooth continuous functions. The use of experimental data to estimate agricultural response surfaces continues, usually with only a small number of inputs [182]. It is not uncommon for fertilizer and feed recommendations in many countries to be generated from such analyses and extrapolated to perhaps quite sizeable areas [21, 134, 164, 200, 205]. Production functions for more complex inputs, such as irrigation water, have understandably been more difficult to develop [105, 123], as have response functions for more intractable outputs, such as milk [161].

3.2 *Stochastic models*

(i) *Response surfaces.* Most recommendations from response surfaces consider the effect of variability of input and output prices on optima, and to this extent a small part of the decision-maker's risk problem is acknowledged, though generally without recognition of probability distributions for variable prices. But there have been few attempts to incorporate the location of the response surface itself as a stochastic variable in response analysis. If this is done, and appropriate price distributions are also included, the resulting risky decision problem can become quite complicated. Not only analytical problems but also experimental difficulties continue to limit progress in this area [7, 57, 66, 162, 181].

(ii) *Utility analysis.* It has long been trite to observe that under risky conditions a decision-maker acts so as to maximize his utility. It may be surprising then that this irrefutable (positive) observation underlies a major area of (normative) decision analysis in agricultural management. The name of the founding guru of this field, Daniel Bernoulli (1700–82) has been immortalized by being attached to modern utility analysis, though history owes a greater debt to the more recent efforts of say, von Neumann and Morgenstern in this area.

Bernoullian decision theory [60] depends on a set of reasonable postulates as to a particular decision-maker's preference orderings for various risky prospects, which postulates, if accepted, imply an identifiable utility function. In turn this enables the maximization of expected utility where probabilities may be defined in objective and/or (more significantly) subjective terms. The formulation of management problems in these terms is particularly apposite in agriculture because (*a*) the decision problems faced by the agricultural firm are probably subject to risk from a wider variety of sources than are those faced by most other sorts of firms, and (*b*) the interactions of the farmers' goals, beliefs and values are of acknowledged importance in agricultural decision problems. The formulation of farm management decisions in these terms has been studied at Oregon State and at the University of California at Davis [86] and in Australia [9, 60, 61, 62, 77, 142, 143] where it has been given a substantial boost by the energy of a group of committed utility maximizers at the University of New England.

Another resurrected hero of decision theory is the ecclesiastical mathematician, Rev. Thomas Bayes (1702–61) whose formula may be used to revise subjective or prior probability estimates in the light of accruing information. His name adorns an area of statistical inference which seeks to replace classical significance testing methods with ones more attuned to subjective and economic criteria. A Bayesian approach has been forcibly promulgated for experimental research and recommendation in agriculture [8, 63, 186]; however, old agricultural statisticians, like boards of directors and military juntas, take a lot of overthrowing. Because Bayes' theorem can be used to revise the probability estimates in a utility-maximizing model, there is a degree of overlap between Bayesian and Bernoullian decision theory; indeed the two terms are sometimes used interchangeably. Applications of 'Bayesian decision theory' to agricultural management problems have continued to appear in the last three years [35, 42, 77, 83, 129].

(iii) *Game theory*. The decline in the application of game theory to agricultural production problems which occurred during the 1960s, has continued in the early seventies, and only games against Nature (literally interpreted) seem to survive [12, 179, 210]. The hypothesis that the fading of interest in this area is due to Dillon's effective 1962 hatchet job is not really testable.* Attempts to incorporate game-theoretic criteria into a programming-based model are considered in section 4.3 (ii) below.

3.3 *Dynamic models*

Dynamic problems in the theory of the agricultural firm have been attacked mainly with programming tools and the use of response surfaces in optimization over time has been limited to some cropping problems such as multi-harvest crops [121] and to livestock feeding systems. In a longer-run context the techniques of investment planning and capital budgeting are established means of solving an important class of multiperiod decision problems in managerial analysis. These methods may be broadened to incorporate utility or risk considerations if an intertemporal utility function can be identified [9, 183]. This area also encompasses some firm growth models whose relevance to the agricultural firm has been assessed [11, 175].

3.4 *Dynamic stochastic models*

(i) *Dynamic programming*. Despite its name, it is more appropriate to consider dynamic programming as of use in decision theory rather than in programming models as defined earlier. It may embrace either dynamic or stochastic elements or both.

Dynamic programming [44] is an optimizing method not subject to restrictions as to stationarity, determinateness, linearity or divisibility, but is nevertheless limited in application, mainly by its computational

* See J. L. Dillon, 'Applications of game theory in agricultural economics: review and requiem', *Aust. J. Ag. Econ.*, **6** *(2), 20–35.*

requirements. Thus its non-trivial use in agricultural production economics has been confined to the sorts of complex problems which are either intractable to other methods of analysis, or which require too great a simplification to fit standard techniques. Such applications include problems in irrigation [14, 37, 68, 199], livestock feeding and replacement [118, 146, 165, 194], pasture and range improvements [36], and farm firm growth [127].

Since the limitations of dynamic programming are such as to constrain its use in all fields, not just in agricultural economics, there has been a general interest in the development of more efficient solution algorithms [214, 215, 217]. In addition, the technique stands to gain more than most from the arrival of new generations of bigger and faster computers.

(ii) *Adaptive control theory.* In principle the techniques of adaptive control theory should provide a fruitful way of looking at normative management problems in agriculture. An adaptive control model typically involves a multiperiod utility function to be maximized subject to stochastic constraint(s). It incorporates an explicit mechanism whereby control may be improved by learning, for example by using accruing information to update the specification of probability distributions contained in the model. A variety of solution procedures may be used including analytical methods, enumerative methods such as dynamic programming, simulation, etc. [119]. In practice the application of adaptive control models to real-world problems is greatly constrained by computational problems, and their use in microeconomics has to date been confined to relatively small problems. However, this is one area where future methodological advances are likely to have a substantial payoff, and the use of these techniques in agricultural economics seems destined to grow.

4. PROGRAMMING MODELS

4.1 *Static deterministic models*

The use of linear programming in farm management decision problems has become standard practice throughout the world; indeed it is now accorded 'classical' status [213, p. 204]. The growth in the pragmatic use of linear programming in agriculture which occurred during the sixties in advanced Western countries is now being repeated elsewhere, for example in Eastern Europe [124, 125, 193, 217, 218] and in developing countries [49, 102, 103, 157]. The majority of these applications are to standard farm planning and feed mix problems, with an emphasis in planned economies on questions of resource pricing and allocation both within and between farms. Meanwhile in the West, there is a continuing effort to improve the real-world application of linear programming. These efforts include attempts to make the technique understandable to an even wider audience of extension workers and farmers [26, 71, 89, 110], the use of parametric procedures to increase the range of applicability of optimal solutions [15, 208], and the development of computer programmes to generate LP matrices from basic technical and economic data and to translate LP solutions into terms comprehensible to the layman [15, 23, 30, 33, 54, 89, 136]. These efforts, combined with the ever-increasing ubiquity of electronic computers, are helping to hasten the departure of the cumbersome quasi-programming manually-computed planning techniques which enjoyed a transient popularity (particularly in Europe) a decade ago.

At a more general level the use of computers for farm management accounting continues to grow [4, 17, 18, 19, 55, 145, 201, 204]. A natural extension of these accounting systems is to incorporate in them some planning or optimization capability. Linear programming and, more recently, simulation are the preferred techniques for this purpose [27, 28, 54, 177].

4.2 *Dynamic models*

The use of dynamic linear programming (equivalently 'multiperiod', 'polyperiod', or 'intertemporal' programming) in agriculture, which was initially explored in the late fifties and early sixties, has continued into the seventies, with attention focused, not surprisingly, on those areas where the time problems are paramount, such as the production of tree and vine crops under irrigation [109], livestock feeding [93, 130], and particularly problems of capital budgeting and optimal firm growth [2, 20, 32, 41, 117, 157, 158, 159, 168]. In the latter field, the difficulties raised by taxation considerations over time [39, 81], by the lumpiness of farm investment alternatives [2, 20] and by problems of multiple objectives [41] have evoked special interest.

The forbidding size of dynamic linear programming matrices has no doubt deterred many a potential user of the technique. In fact it is probably true to say that practical application of DLP is more constrained by our unwillingness or even our inability to construct the necessary matrices than by the computer's capacity to solve them. Nevertheless, general efforts to improve the solubility of large-scale systems continue [79], for example by *ad hoc* simplification based on pragmatic features of particular dynamic problems [216].

4.3 *Stochastic models*

Programming models involving stochastic elements have been one of the most popular areas of endeavour for agricultural production methodologists, for two main reasons: (*a*) the undoubted variability of planning parameters in reality greatly weakens the realism of deterministic models; and (*b*) the fact that farmers do have an attitude to risk as well as to profit means that the variability as well as the size of payoffs is an important component in farm decision analysis.

(i) *Simple approaches.* The simplest and most direct approach to looking at variability in programming models is via the enumerative methods of sensitivity analysis [155] and parametric linear programming [184]. In the first instance at least, these approaches are not probability orientated, but simply aimed at gaining a 'feel' for the response of solutions to variations in parameters. However, this sort of parameterization tends to become unwieldy unless some special conditions can be imposed [78].

A closely related area is 'suboptimal programming', a term open to semantic quibble [16, 166]. In this approach, the solutions to a linear programming problem within a certain profit range of the overall optimum are examined, and a choice between them made on the basis of other criteria such as risk [188] or some more general combination of objectives [148]. Practical applications of suboptimal programming continue to appear [76].

(ii) *Decision theory in a programming context.* It has been suggested that the problem of choice between linear programming solutions may be formalized using decision or game theory methods. The direct incorporation of such decision criteria into a linear programming model is generally referred to as 'maximin programming', though it need not be restricted to the use of the Wald maximin criterion alone [31, 88, 94, 98, 103, 115, 116, 137, 179, 198]. The choice problem in these studies is usually framed in terms of the trade-off between expected income and its variability, a problem amenable to formulation and solution by quadratic programming.

(iii) *Quadratic programming.* This well-known technique, involving the extremization of a quadratic function subject to linear constraints, has been applied to risky decision problems where maximum expected income and minimum income variance are assumed to be the decision-maker's conflicting objectives. Agricultural applications following the original work of Markowitz and Freund were initially sparse, owing mainly to the unavailability of efficient computer programmes. In more recent times, however, the number of farm management applications has increased [22, 106, 167, 169, 185]. Nevertheless, because of these computational difficulties, attention has been paid to developing simplified formulations which preserve the essential features of the E-V problem but which allow better computability via direct calculation methods [149] or through separable or parametric linear programming procedures [47, 48, 95, 96, 97, 98, 120, 141, 202, 203].

(iv) *Stochastic programming.* This is a generic term covering a variety of means of introducing random elements into the objective function, technical coefficients and/or constraint levels of a programming model [187]. Many of the alternative formulations (e.g. chance-constrained programming, etc.) have had their actual or potential application in agriculture explored [29, 87, 170, 171, 172]. One promising recent line of development has been the combination of the E-V choice problem with discrete stochastic programming, allowing the treatment of uncertainty in relation to objective functions, input–output and resource constraint coefficients simultaneously under plausible assumptions [139] (see further section 4.4 below). Another approach is through the formulation of imperfectly-specified ('fuzzy') constraints or goals [25], a notion which would appear to have some descriptive realism in agriculture.

4.4 *Dynamic stochastic models*

Given the analytical and computational difficulties associated with incorporating dynamic and stochastic elements separately into programming models, it is hardly surprising that models containing both dynamic and stochastic features have to date been relatively rare. Although conceptually such models are not difficult to build, some simplification is essential if they are to have any practical solubility. For example, dynamic aspects may be treated using decomposition methods, whilst the uncertainty aspect may be looked at in terms of, say, ruin-avoiding strategies [32, 216] or the more general methods of stochastic programming referred to above [39, 168]. The use of discrete stochastic programming is particularly appropriate in the context of sequential decisions under uncertainty [171] and the incorporation of Bayesian decision theory (e.g. to evaluate the worth of acquiring new information) into such models is relatively straightforward and potentially fruitful [170].

The area of dynamic stochastic models is one field where simulation has made great headway, even though a strict optimizing approach may have to be sacrificed. Such models are considered in section 5 below.

4.5 *Other programming models*

The other major type of programming model of interest to agricultural production economists has been integer programming where one or more variables in a programming model are constrained to whole-number values [213]. Here again, widespread application has awaited the development of improved computation facilities, in terms of both soft- and hard-ware [38, 80]. Meanwhile, agricultural applications continue to appear wherein the integer variables are mainly lumpy farm investment activities [51, 189].

5. SIMULATION

A simulation model may contain some or all of the following features: a large number of variables and functions, stochastic elements and their distributions, many parameters to be specified or estimated, many linkages between the various elements in the model, non-linearities and discontinuities, various constraints, and dynamic and feedback mechanisms. A simulation model which represents adequately some real world system may be subjected to a series of trials in order to generate time paths and/or distributions of variables of interest to the decision-maker. Typically the stochastic components are introduced via sampling from appropriate distributions, whence is derived the name 'Monte Carlo', a phrase sometimes used synonymously with 'simulation'. In fact, simulation has a wider interpretation, incorporating any exercise where a model is subjected to some form of experimentation such that its behaviour may be observed. Simulation has been long used to obtain solutions in mathematics when analytical methods fail or are inappropriate [107, 203].

We have already noted the importance of dynamic and stochastic elements in farm decision problems. Add to this the technical complexity of the biological processes involved in agricultural production and it is easy to see why simulation has been so eagerly applied in agriculture [46, 111, 192]. These applications may be divided into partial systems, whole-farm systems, and gaming applications.

5.1 *Partial systems*

By 'partial systems' we mean some specific aspect of farm organization, where the operations of the farm which are irrevelant to the specific decision under study are ignored. Such applications include livestock processes [138, 206], crop processes [43], irrigation timing [156], and investment in, or replacement of, farm machinery and equipment for irrigation, harvesting, etc. [10, 56, 67, 74, 75, 82, 122, 150, 160, 195]. In all of these applications, a basic model of the subsystem is constructed and its behaviour in a stochastic environment examined. The results may indicate optimal or near optimal strategies, or may be simply enumerative of the likely range of outcomes which might be expected in the real-world situation.

5.2 *Whole-farm systems*

(i) *Programming-based models.* A simulation model may be used as a component in an ordinary linear programming model in order to generate coefficients not obtainable easily by other means [207]. Again, simulation offers a means of post-LP analysis, i.e. of studying the likely effects of implementing optimal plans derived by ordinary linear programming [137].

A technique introduced to agricultural methodologists during the sixties is a method for farm planning which essentially views the production system of the farm as a linear constraint set, but uses Monte Carlo methods to explore a range of feasible plans. The choice between plans might then be made with their risk attributes in mind. This method, known as 'Monte Carlo programming' is closely related to suboptimal programming and to some forms of stochastic programming, and may easily contain integer restrictions as well. Discussions of this method and applications to real problems continue to appear [50, 51, 65, 90, 110, 128, 151, 201, 212].

(ii) *Systems models.* The systems approach to problems focuses on systems taken as a whole rather than on their parts taken separately [1, p. 661]. A general model of the agricultural firm may be constructed in which the biological, economic and even sociological subsystems and their interactions are represented [27, 28, 58, 59, 104, 108, 114, 190]. The analysis is usually exploratory rather than optimizing and thus the models contain no formal algorithm—their performance is assessed by subjecting them to environmental variation under controlled experimental conditions. Systems methods offer the most general and realistic models of farm firms currently being built. Because their structure is so flexible, they can be made to incorporate many of the desirable features of other model types.

Although, as noted earlier, simulation *per se* has been widely used in agriculture, its application to complete systems in the sense defined above is relatively recent. Large-scale agricultural sector models have begun to be constructed [133] and micro-level applications have now started to appear [52, 58, 126].

At present, the problems limiting the application of systems methods include cost [64] and theoretical problems of verification and validation of models* [5, 6, 209]. However, it seems that with further theoretical work (e.g. on introducing optimizing criteria into systems models [154] and with wider empirical experience, a substantial growth can be expected in the application of systems methods in agriculture.

5.3 *Gaming*

The distinction between simulation and gaming is that the latter involves human players; i.e. a 'game' is set up (which may contain a simulation model of, say, a farm), and the player or players behave in a decision-making capacity, in some role specified by the nature of the game. The participants are thus actors in a drama in which they compose their lines as the play progresses. Although a developed methodology and theory of gaming hardly exists, it is 'beginning to evolve' [191, p. 37].

The main usefulness of gaming in farm management is agreed to be educational [131, 132, 153] although as a teaching device it can be rather costly. Agricultural advisers, extension workers, commercial representatives, administrators and farmers themselves are the main people likely to benefit from playing farm management games. Recent applications of farm management games have been made in U.S.A. [211], Denmark [152], Spain [178], and elsewhere.

6. CONCLUSIONS

For expository convenience in this paper, we have, like other reviewers in this area [6, 113, 144, 173, 213] adopted a classification of the types of models used in agricultural production economics. As we have seen, attempts to break down unrealistic assumptions in the traditional model of the agricultural firm have often proceeded on more than one front at a time, thereby thwarting efforts to devise a watertight taxonomy of models. The end result may well be the development of models of such generality that the construction of pigeon holes will become entirely irrelevant.

Indeed, it can be predicted that a major line of methodological research in the next few years will be the further development of models

* Verification is defined as 'the determination of the rectitude of the completed model *vis-à-vis* its intended algorithmic structure' and validation as 'the comparison of responses emanating from the verified model with available information regarding the corresponding behaviour of the simulated system' [147, p. 18].

incorporating sequential and adaptive elements, probability distributions (objective and/or subjective) for important stochastic variables, and objective functions with emphasis on utility considerations rather than on simple profit maximization. The portrayal of the production conditions of the firm will be in the form of a set of constraining inequalities, or a set of non-linear response functions, the choice of form being governed to some extent by whether the model is explicitly optimizing (in which case programming formulations might be preferred) or whether it is simply exploratory. In fact, even the latter distinction will become blurred, as better methods are devised for discriminating amongst the results of simulation runs.

These developments will incorporate many of the advantages of models discussed herein. An emphasis on management, the role of information, and behavioural aspects will help meet some of the criticisms of more conventional 'market-oriented' models [73, 173, 174, 175, 176]. A closer relationship between agricultural scientists and economists should emerge as the demand for models of complex biological subsystems grows; this in turn can be expected to have a feedback to technical agricultural research [13, 58]. Data problems will, of course, continue, not the least being the estimation of the probability distributions for imperfectly known parameters and variables [9].

The multidimensionality of managerial goals is now well recognized [72, 176]. Multiple goals may be built into models when they can be represented as constraints on decision variables, but the extremization of several objectives still present problems [24]. Tangency solutions exist in principle, and they may even be empirically identifiable in simple cases [148], but the analyst is still largely constrained to presenting a range of solutions to the decision-maker, amongst which he may choose on the basis of some implicit but unidentified indifference system [69]. The introduction of utility concepts into models is a step towards resolving these problems, but there are still many difficulties to be overcome [9, 60, 61].

Nevertheless, concentration on goals in the theory of the firm has diverted attention from questions of values [113]. With increasing involvement of the economics profession at large in the social values implicit in normative economic analysis, it cannot be long before such considerations affect research in agricultural production economics [40, 45, 84, 99, 112, 180].

Some writers advocate the development of many small theories and models directed at specific problems, rather than of large-scale general theories and models as forecast above [73, 113]. This dichotomy is seen as related to the distinction between 'problem-oriented' and 'technique-oriented' research, the latter being often considered at variance with some notion of 'correct' scientific method. Yet 'technique-oriented' research in the past has shown a remarkable ability to come up with methodologies of considerable use in solving real-world problems. Likewise, large models can be seen as collections of smaller ones; thus the development of large-scale systems is not inconsistent with the continuing study of particular problems with a variety of specific methodologies.

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