AN EMPIRICAL INVESTIGATION OF THE HARVEST OPERATION USING SYSTEMS SIMULATION

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A simple model of the cereal harvest operation was constructed for the Wimmera region of Victoria. The model was used to investigate factors influential in determining the harvesting costs of a machinery system over a period of years. An evaluation of alternative machinery systems was also conducted using the model. The superiority of systems simulation over static analysis was demonstrated by using the model to incorporate stochastic variables and to handle the dynamic nature of the harvest operation. In addition, the model output was shown to provide more information for decision makers than had resulted from previous Australian studies. It was concluded that systems simulation is an appropriate technique for investigating farm management machinery selection problems.

Introduction

The potential of systems analysis in agricultural management problems has been demonstrated by the investigations presented in Dent and Anderson [4]. The procedure has gained ready acceptance in machinery system studies, especially in grain harvesting systems. Investigations of harvesting systems employing systems analysis have been conducted in England by Donaldson [5] and [6] and by Dalton [3], in Canada by Donaldson [7] and in the Netherlands by van Kampen [11].

Many diseconomies in agriculture arise from the untimeliness of operations. The costs incurred by a given machinery system vary from year to year depending in part on weather conditions. To add to the complexity, the losses associated with untimeliness are often ill-defined and researchers find them difficult to specify and incorporate into an analysis. In many static analyses, researchers circumvent the penalty costs of untimeliness. For example, Donaldson and McInerney [8] in England and J. G. Ryan [13] in Australia, in their investigations of the harvesting operation constrained the acreage associated with different headers. They made the assumption that losses were negligible for the different headers up to the respective acreage levels. The acreage levels or 'capacities' were assigned to each header on the basis of average work rate and number of hours available for harvesting during the set harvest period. Weather variability is commonly incorporated into static analyses by determining the 'capacities' in acres, of each header in 'good', 'average' and 'poor' harvesting periods. The short-run cost curves obtained

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are L-shaped and generally do not intersect over the acreage range investigated. Consequently the long-run cost curve derived from the short-run curves has a 'saw-tooth' appearance as the 'jumps' to the next larger machines occur. Donaldson and McInerney [8, p.180] and J. G. Ryan [13, p.149] provide examples of short-run and long-run cost curves obtained without the inclusion of penalty costs.

In the United States, Heady and Krenz [10] included penalty costs in their investigation of machinery combinations on Iowa farms. The short-run cost curves they obtained were akin to the classical U-shape curves of the text-books. Heady and Krenz [10, p. 461], allowed for weather variability by categorizing an historical sequence into five weather groups and then calculated the net returns for a machinery combination at various acreage levels. By weighting the return in each weather category by frequency, an expected value of net return at each acreage level was obtained. This procedure provided more information than the static analyses had done for selecting an acreage for a machinery combination, however the computational load was greater and the analysis was still based on simplistic assumptions.

A systems simulation approach can aid the researcher investigating a complex operation such as harvesting, which depends on the interaction of biological, physical and environmental factors. A computer model can be built to incorporate the dynamic aspects of harvesting and the stochastic variables can be specified as density functions, instead of as single valued, deterministic variables. A pseudo-random number routine is used to sample from the density functions to provide values for the variables in the harvest model. The model may be run over a number of 'years' to investigate the performance of a given machinery system. Each 'year' provides a new set of harvesting conditions. Parameters may be altered to determine their effect on the system with little addition to the computational load of the researcher. The results obtained are not limited to single values but may be presented as density functions. To elucidate similar information from field experiments would be infeasible.

This paper presents a model of the harvest operation for the Wimmera region of Victoria. The methodology employed was derived from the work done by Donaldson in England [6] and from his more advanced treatise in Canada [7], and applied to Australian conditions. Van Kampen [11] constructed a model of a 20,000 hectare grain farm in the Netherlands and included detailed relationships of weather and moisture content for various grains. The model was used to study the chain of operations involved in the organization of the harvesting, transportation, drying and storage of the grains with a number of headers and ancillary equipment. The model employed by Dalton in England [3], was concerned with the relationship between harvesting moisture content, drier capacity and header work rate. The Wimmera model is simpler than the overseas models, in that grain driers are not included, therefore much less meteorological data were required. The model is conceptually similar to those used by Donaldson [6] and [7], but is operationally distinct. The model was used in identifying the parameters influential in determining the costs of harvesting and in evaluating a contract (CON) harvesting system, a power-take-off (PTO) harvesting system and a self-propelled (SP) harvesting system.

The Problem

Harvesting equipment represents approximately one-third of the depreciated total cropping plant value in the Wimmera [2, p.86]. Headers are the principal component of the harvesting equipment investment figure, due to their high purchase prices. The farmer, when selecting the harvesting system for his crop acreage, has to choose between the use of contract services, between the purchase of large machines of high capacity and high overhead costs and the purchase of less costly, lower capacity machines which would allow his crop to remain exposed to the environment for a longer period of time. The choice depends on the contract harvesting rate, on the overhead costs of headers and on the variable costs, including the penalty costs of untimeliness.

The weather is an important determinant of the time required for completion of a given acreage and of the associated risks of grain loss and damage. However, weather is not the only stochastic factor affecting the harvesting process. Other factors such as crop yield, crop condition, work rate, length of working day and holdup times all affect the harvesting operation to a different extent each year. The result is that there is no unique cost of harvesting a particular acreage with a given machinery system. Instead the cost varies with the physical and the yearly environmental factors, to give a distribution of costs over time. Each machinery system will have associated with its per-unit cost curve a theoretical distribution of per-unit costs determined by all possible interactions between the factors affecting the harvesting cost. Estimates of these distributions for alternative machinery systems will place the farmer in a better position to make his selection. In addition the estimates will allow him to use decision criteria other than minimum expected cost per acre.

Model Description

For each machinery system, the model calculates the costs of harvesting wheat crops over a range of acres[1]. The variables incorporated in the model fell into the following categories:

(i) weather constraints—
- (a) length of harvest period
- (b) non-harvestable days
- (c) grain weather damage

(ii) biological factors—
- (a) crop yields
- (b) grain losses from ripe heads

(iii) characteristics of the machinery system—
- (a) fixed costs
- (b) operating costs
- (c) rate of work
- (d) time allowed per day

[1] The model does not include any grain disposal system from paddock to storage. It was assumed that the farmer could carry out this work outside of the time allowed for harvesting each day.

Rainfall data, which was available for 43 years was recorded in the Wimmera at Longerenong Agricultural College (L.A.C.) and was used in determining the annual harvesting weather patterns[2]. Estimates on delays in harvesting time due to rainfall were provided by agronomists. The days during the harvest period (23rd December to 6th February) were coded as full, half or non-harvesting days for inclusion in the model. In addition, if 6 consecutive days were classified as full days, the 7th was declared an off-day irrespective of weather. Grain damage resulting from rain, as distinct from shedding losses, was estimated by agronomists and coded in sequence with the pattern of harvesting days.

Long-term rotation trials at L.A.C. were used as a basis for deriving a cumulative density function of crop yield. In the operation of the model this function was randomly sampled each year to obtain the crop yield[3]. Grain shedding losses from the mature, unharvested crop acres were estimated by farmers and by agronomists. No empirical work in Australia was available on the nature and extent of these losses[4].

The details of the characteristics of the machinery systems were based on information recorded daily for one harvesting season by 23 farmers in the Wimmera in tractor and autoheader log books [14]. Operating costs, repair histories and harvesting rates for three machinery systems as well as time worked per day and a distribution of holdup frequencies were derived from these log books and from farmers' cash books. The maximum time permitted for harvesting was 6.8 hours per day. An additional hour was allowed for setting up etc. giving a total work day of 7.8 hours. The day length corresponded almost exactly with the average harvest day found over two seasons by Brown and Vasey [1, p.48] in their investigation in the Victorian wheat areas.

A reasonably detailed flow chart of the model is presented in Figure 1. For a given machinery system the costs of harvesting at specified acreage levels up to a maximum acreage level were calculated. At the beginning of each year a crop yield was selected and paired with a harvesting pattern. Computations were performed on a daily basis and each day's information, as coded in the harvesting pattern for that year, was examined in sequence. If harvesting were possible on the day considered, the work time, net of any delays, was determined and the area harvested calculated. Machinery operating and labour costs were computed and the costs of grain shedding losses on all acres remaining unharvested were included. If harvesting were not possible on that day, the cost of grain damage, if any, due to heavy rain, was calculated.

[2]Phillips [12] has criticized the use of historical data as an unnecessary restriction on the generality of a model. However, historical weather patterns can be viewed as a sample provided by nature compared with a sample generated by a computer routine. The former does not have the computational and validation problems of the latter. Harvesting costs for a given year are independent of the preceding year's weather, relying only on the intra-year weather pattern. Therefore, the sequence of yearly weather is not important in this study and providing sufficient observations are available to provide intra-year patterns, the historical data should be sufficient.

[3] It was assumed that rainfall during the harvest period was independent of factors influencing crop yield, i.e., principally rainfall during the crop growing season.

[4] Donaldson [6] reported grain shedding loss investigations in Sweden [9]. The size of the Swedish losses fluctuated with days after maturity. The levels were near the estimate used for the Wimmera of 0.36 per cent per day.

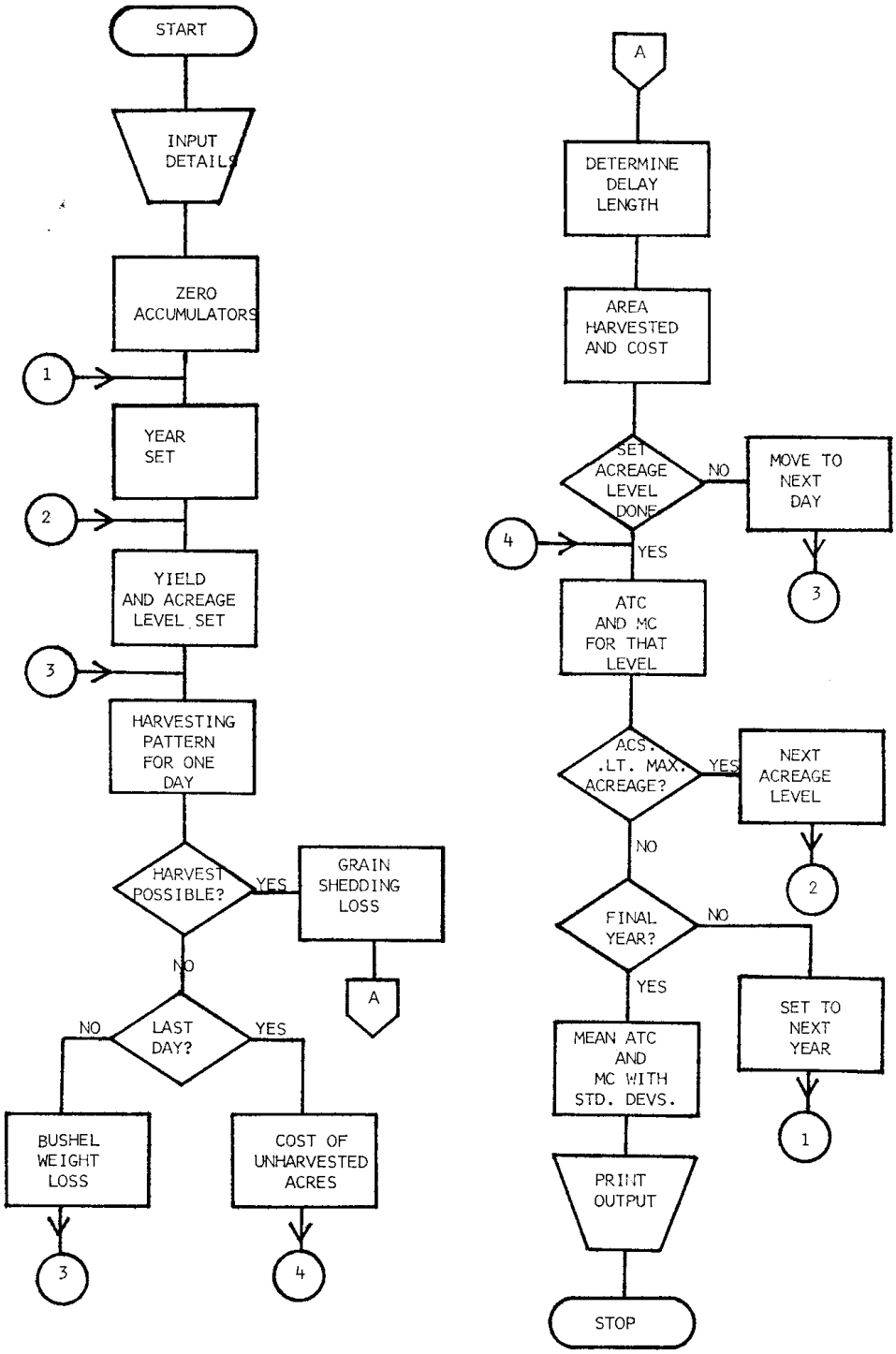

FIGURE 1
Flow Chart of the Harvest Model

These daily computations were continued up to the specified acreage level, at which the overhead costs of the machinery system under consideration were included. The average total cost (ATC) at that acreage level and the marginal cost (MC) between that acreage level and the level below it were calculated. The model was set to the next higher acreage level and the process was repeated with the same year's harvesting pattern and crop yield. The calculation of ATC and MC at each acreage level continued until the maximum acreage was reached. In some years, due to unfavourable weather conditions, the harvest period expired before the acreage level under consideration could be harvested. When this occurred, a standard charge, ($3 per acre), approximating the contract rate was levied on all unharvested acres. Once the maximum acreage was obtained, the next year's harvesting pattern was taken and another crop yield selected. The calculations commenced once more at the lowest acreage level. The computations continued until all the 43 yearly harvesting patterns were exhausted. The mean ATC and mean MC were then calculated at each acreage level from the 43 values stored, one from each year.

The output at each acreage level contained the mean ATC, the standard deviation of the ATC, the mean MC and the frequency with which the machinery system exceeded the set harvesting period over the 43 years. In addition, frequency distributions of ATC's were obtained at a number of specified acreage levels.

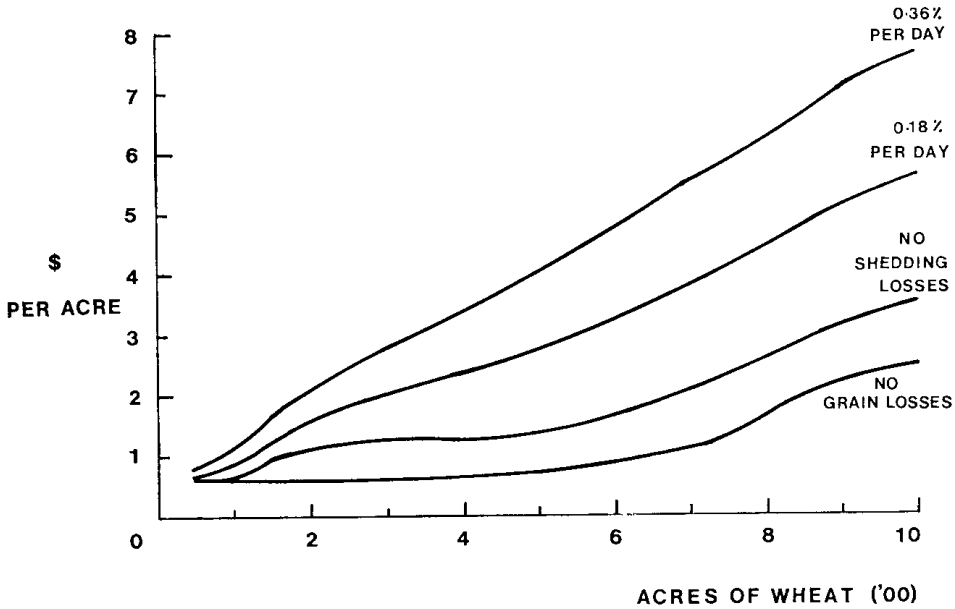

Figure 2
The Effect of the Different Components on the Mean MC Curve—PTO System

The Components of Harvesting Cost

Four main components of cost were considered in the model. They were machinery and labour costs, grain weather damage, grain shedding costs and the standard per acre charge if the specified harvesting period were exceeded. The influence of the costs varied with acreage. Figure 2

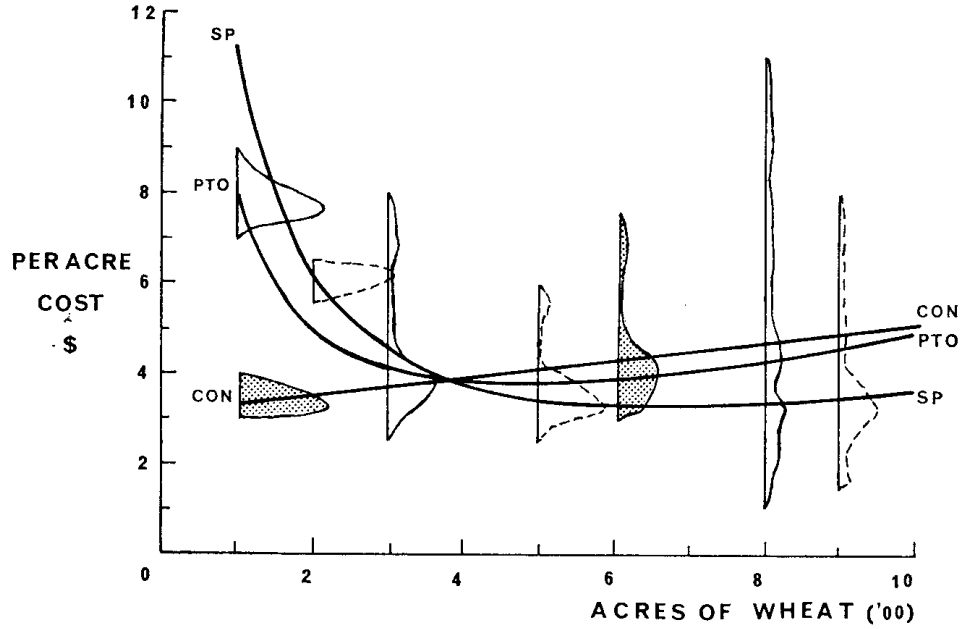

FIGURE 3
Mean ATC Curves and ATC Density Functions for each System

shows the effect of the cost components on the mean MC curve for one system, the PTO system (see Table 1). The 'no grain losses' curve incorporated the cost for machinery and labour as well as the non-completion charge. The curve was nearly linear up to 500 acres, fluctuating slightly due to variations in work rates and delay times. Over 500 acres the standard charge for unharvested acres became increasingly important as in more and more years the harvesting period was exceeded. The frequency with which this charge occurred is given in Table 2 and rose from 10 per cent of years at 600 acres to 77 per cent at 1,000 acres.

The 'no shedding losses' curve included the penalty costs resulting from grain weather damage, but included no daily shedding of grain from the ripe heads. The losses from rain damage became evident after 100 acres, demonstrating that in some years inclement weather occurred very early in the harvesting season. The weather damage represented approximately 50 cents per acre at 150 acres and gradually rose to $1 at 1,000 acres.

The losses incurred through the shedding of grain from mature, unharvested acres were the largest single cost component. These losses were present at the lowest acreages and caused the mean MC curve to rise immediately. Rates of daily loss less than the estimated 0.36 per cent of the crop yield would lower the mean MC curve. The 0.18 per cent curve in Figure 2 illustrated the effect of halving the shedding rate loss. The size of the shedding losses was therefore very important in determining the harvesting costs of a particular system. Yet, empirical evidence on their nature and extent was not available in Australia[5]. The

[5] All major wheat research centres in eastern Australia were approached in an endeavour to elucidate the nature and extent of these losses. Replies were in very general terms and revealed that no quantitative observations were available.

validity of the loss assumption used in this study rests on the subjective estimates obtained from agronomists and farmers. Farmers' opinions on losses in the Wimmera varied from practically zero loss to unspecified large amounts, which some maintained would occur if harvesting were not completed as quickly as possible after the crop ripened. A problem associated with the farmers' estimates was that with the large capacity machines they have been using for a number of years, crops have not been left standing long enough for them to know what losses occur after a month or six weeks.

If the time permitted for harvesting were increased from 6.8 hours to 8.8 hours per day and daily shedding losses remained at 0.36 per cent of the crop yield, the 8.8 hours MC curve would fall between the 0.36 per cent and 0.18 per cent curves of Figure 2. (The 8.8 hour curve has not been included in the figure). The 8.8 hour curve would be 30 cents below the 0.36 per cent curve at 250 acres, 60 cents below at 500 acres and $1.25 below at 750 acres. The two hour per day increase in time allowed for harvesting would permit a larger acreage of crop to be harvested in a shorter time period, with a consequent lowering of the penalty costs. The use of a larger capacity system than the PTO would also lower the penalty costs for a given acreage, but would have higher overhead costs.

Alternative Harvesting Systems

Descriptions of the three machinery systems considered are contained in Table 1. The machinery systems selected were based on the types and sizes of headers encountered in the Wimmera machinery study [14]. The maximum daily harvesting time for the contract system, CON, was two hours greater than for the other systems. This assumption was based on two considerations. Firstly, the most common time spent harvesting each day, as recorded in the log books after the 6.8 hour figure was 8.8 hours per day. Secondly, contractors have an incentive to work their plant as long as possible as they are paid on acres harvested and a plant lying idle is non-productive for them. Owner operators, on the other hand, may leave their plant idle whilst they cart their grain to the silo.

A comparison of the ATC curves obtained for the three alternative systems are shown in Figure 3. All curves are based on the assumption that harvesting commences on the day of maturity. The two systems involving ownership of the headers display a shape similar to the theoretical U-shape of the ATC curves. Initially overheads are spread over more and more acres causing a decline in ATC. However, the rising untimeliness costs counter this effect and cause the ATC curve to pass through a minimum and then to slowly rise.

The CON system was the least cost alternative up to 400 acres, after which the SP system became the least cost choice. However, a farmer may not want to use a contract system. The PTO system would then become the choice up to 400 acres. Perhaps the least cost criteria is not the relevant decision guide. A farmer may desire a system which gives him the lowest maximum ATC at his acreage level, the least variability of ATC or a system which will finish his harvest within a specified time period in a set proportion of years. Table 2 contains a summary of the

TABLE 1

Alternative Machinery Systems

System Description	PTO 12' or 14' Power-Take-Off header	SP 15' Self-Propelled header	CON Contractor using a 15' SP header
Overhead costs per yr.	$709	$1077	-
Labour	$1.20 per hour	$1.20 per hour	-
Operating costs	70.5 cents/hr.	49.4 cents/hr.	$3/acre plus 10 cents per bag above the first 10 bags [15, p. 10]
Av. work rate per hour	3.7 acs/hr.	5.3 acs/hr.	5.3 acs/hr.
Maximum harvest time per day	6.8 hrs.	6.8 hrs.	8.8 hrs.

Source: T. J. Ryan [14]

output for each system and provides information relevant for decisions based on criteria other than least cost per acre.

At the 400-acre level, the three systems have an almost identical mean ATC. However, the standard deviations differ, with the PTO system having a much larger standard deviation. The PTO system is also approaching the acreage level above which it fails to complete the harvest within the set period in all years. The other systems are operating well below this limit. The SP system has a much lower mean MC at the 400 acre level than the other two. If future expansions of crop acreage are planned this would be an important consideration, since extra acres could be harvested at a lower cost than with the other two systems. At the 400 acre level the SP system would be a logical choice since it would finish the harvest more quickly than the PTO, it has less variability in ATC over time, and economies of utilization can be achieved when and if acreage were expanded.

The density functions of ATC's obtained over the 43 years for the three systems are shown in Figure 3 at right angles to the mean ATC curves. As each system is extended over more and more acres, the distributions become more dispersed. The occurrence of a small number of 'bad' harvesting years (high cost years) is clearly demonstrated by the long tails formed by the distributions. The selection of a system on lowest maximum ATC basis may be unnecessarily conservative as that basis or decision criterion is dependent on the few observations at one extreme of the density function and disregards other information. Consider Table 3. If a farmer were choosing between the PTO and the CON systems at 600 acres and using the lower maximum ATC criterion he would select the CON system, with a maximum ATC of $7.25 compared with $9.75. However, it can be seen that while the farmer would avoid the excessive harvesting costs incurred by the PTO system in the few

TABLE 2

Wheat Harvest Costs — Alternative Systems

Acres	Mean ATC	Std. Dev. ATC	Mean MC	Freq.[a]	Mean ATC	Std. Dev. ATC	Mean MC	Freq.[a]	Mean ATC	Std. Dev. ATC	Mean MC	Freq.[a]
	$	$	$		$	$	$		$	$	$	
		PTO SYSTEM				SP SYSTEM				CON SYSTEM		
100	7.94	0.26	1.07	0.00	11.27	0.07	0.59	0.00	3.33	0.26	3.43	0.00
200	4.88	0.76	2.14	0.00	6.05	0.14	1.04	0.00	3.46	0.30	3.70	0.00
300	4.11	1.14	2.83	0.00	4.48	0.33	1.61	0.00	3.67	0.45	4.20	0.00
400	3.88	1.41	3.44	0.00	3.84	0.55	2.09	0.00	3.89	0.64	4.62	0.00
500	3.87	1.63	4.03	0.05	3.53	0.73	2.42	0.00	4.10	0.83	4.88	0.00
600	3.97	1.83	4.70	0.09	3.38	0.87	2.78	0.00	4.31	1.01	5.22	0.00
700	4.16	1.99	5.52	0.21	3.33	0.98	3.13	0.02	4.50	1.15	5.51	0.00
800	4.37	2.12	6.22	0.37	3.36	1.12	3.90	0.05	4.67	1.27	5.81	0.00
900	4.65	2.23	7.16	0.65	3.45	1.25	4.31	0.07	4.85	1.37	6.10	0.02
1,000	4.92	2.30	7.60	0.77	3.57	1.37	4.79	0.14	5.01	1.45	6.47	0.02

(a) Frequency with which the set harvesting period (23rd Dec.—6th Feb.) was exceeded.

'bad' harvesting years, by employing the CON system, he would also miss out in a high proportion of 'low' cost harvesting years offered by the PTO system. In 13 of the 43 years (30 per cent), the ATC of the PTO system was less than the minimum ATC of the CON system. Only in 3 years did the ATC of the PTO system exceed the maximum ATC of the CON system. The mean ATC and the mean MC of the PTO system are both lower than the mean ATC and mean MC for the CON system (see Table 2.). The lower mean MC of the PTO system would be advantageous if an extension of wheat acreage were planned in the future. When deciding between alternative machinery systems all available information should be incorporated into the decision analysis.

TABLE 3

Frequency of Occurrence of Harvest Costs at 600 Acres

COST PER ACRE (a) $	PTO No. of years	CON No. of years
1.75	3	
2.25	4	
2.75	6	
3.25	8	8
3.75	8	11
4.25	4	14
4.75	2	5
5.25	3	
5.75		
6.25		
6.75	1	3
7.25	1	2
7.75		
8.25		
8.75	2	
9.25		
9.75	1	

(a) Mid-point of 50 cent interval.

Discussion and Conclusions

The model considered in this paper encountered two of the major problems which confront systems simulation. The first problem was scarcity of data. The second problem was that of validating the model. The output from the model highlighted the sensitivity of the analysis to the daily grain loss estimate. Until some empirical data relevant to Australian conditions becomes available, the only alternative is to seek the subjective estimates of agronomists and of the farmers concerned. Since it is the farmers who have to make the final decision, they must make some estimate of their own as to the probabilities and the extent of grain losses associated with untimeliness of harvesting. If necessary, the researcher can provide results incorporating different estimates of losses for different farmers, or groups of farmers.

One advantage claimed for systems simulation is that it focuses attention on areas of inadequate data and can influence research projects to investigate these areas. In the case of the present study, this claim is

being fulfilled. The Victorian Department of Agriculture agreed to an investigation of grain shedding losses at Rutherglen Research Station. The results are not yet available.

Validation of the model rests primarily on the veracity of the estimates of delays due to rain and to the grain loss estimates. Empirical information on delays after rain was lacking and the estimates of agronomists were used. Similarly, quantitative data on grain losses were lacking and estimates of farmers and agronomists were used. The model was constructed in a logical manner, empirical data were used wherever available, otherwise guestimates from experienced personnel were employed. The model itself is relatively simple and as more information becomes available the model can be further refined. The model has practical application and could be applied with immediate benefits to an evaluation of syndicated ownership of headers and to other types of harvesting systems. With adjustment, a grain drier could be included and the model used to assess the feasibility of driers, perhaps in the, at present, marginal cropping areas. In this paper only one crop, wheat, was considered. But, providing loss functions can be specified, the model could be applied to other crops, such as barley, oats or to combinations of crops.

It is concluded that a systems simulation approach is ideally suited for the examination of harvesting machinery costs. The model specification demands inclusion of relevant variables which may not have been considered adequately in previous Australian studies. The data requirements demand careful attention to the relationship between variables and highlight deficiencies of important parameters or relationships. Stochastic variables, which are the 'real world' in agriculture can be incorporated. The information available from the model, particularly the density functions, gives more details of a systems performance and behaviour under differing environmental conditions than available from a static cost analysis. The acceptance and use of systems simulation in farm management problems will help counter the oft heard farmer criticism " . . . that's all right for an average year, but every year's different."

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