MECHANICAL HARVEST SYSTEM SIMULATION AND DESIGN CRITERIA FOR PROCESSING APPLES

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

GALEN KENT BROWN

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J B Holtman
Major professor

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ABSTRACT

MECHANICAL HARVEST SYSTEM SIMULATION
AND DESIGN CRITERIA FOR
PROCESSING APPLES

By

Galen Kent Brown

The primary objectives of this study were to design a harvest simulation model for use in evaluating mechanical harvest systems proposed for processing apples and to develop a technique for specifying the needed values of the harvest system design parameters so that the harvest system will be of economic benefit to nearly all of the growers included in the simulation.

The four apple varieties with the largest processed volume (standard type trees in acreage proportions determined from published data) were assumed to be representative of production for the individual grower.

The discrete time form and a simulation time increment of one day are used in the harvest simulation model. Known functional relations between yields, harvest cost, and crop income were used to insure realism in the economic behavior of the model. Separate stochastic models were designed to describe annual yield; daily windloss; and

daily work time lost due to Sundays, rain, or machine breakdowns.

The yield model for each variety was formulated as a first-order autoregression relation having negative correlation between yields for successive years. Using this approach the biennial bearing tendency as well as the probability distribution of annual yield is adequately described for harvest simulation. A mean value for daily growth rate, estimated from growth data, was included in the simulation model.

The daily windloss model for each apple variety was formulated as a non-linear function of daily average wind velocity. Parameters for this relation were derived using iteration to satisfy the requirement that simulated windloss must closely match the probability density function and expected value for annual windloss. The parameter values were different for each variety. Relations between windloss and wind velocity were not available in the literature.

The model for daily lost work time consists of separate models for including the effect of Sundays, rain, or machine breakdowns. The first Sunday of each season occurs at random within the first seven days, followed by successive Sundays at seven-day intervals. The lost time value for rain is generated using the cummulative distribution function for lost time, derived from historical records of hourly rain observations and a no-work criteria based on the amount of rain. The model for machine breakdowns assumes that operating time between breakdowns is exponentially distributed.

Harvest rate--acreage relationships were determined for the Grand Rapids area of Michigan. In 90% of the seasons, a harvest system with a harvest rate of 10 trees per hour will be able to handle up to 70 acres of standard type apple trees. A change in acreage requires a proportionate change in harvest rate.

A general policy of delaying the start of harvest in order to increase the harvested volume, anticipating that fruit sizing may be greater than windloss, was evaluated by simulation. This policy was not beneficial because the expected value of harvested volume decreased, except under conditions of sustained rapid fruit growth.

The harvest simulation model HARVSIM was designed to evaluate proposed mechanical harvest systems. A simulation for the period 1968-1971 showed that expected margin (a measure of economic benefit) for two assumed mechanical harvest systems increased while the probability of negative margin decreased each year.

A sensitivity analysis was performed to identify critical parameters in the design or operation of the harvest systems. The analysis showed that small variations in harvest rate, machine recovery, and fruit injury, for these mechanical harvest systems cause large variations in expected margin and expected planning margin. The analysis also showed that similar results occur for variations in yield and hand picking cost--thus these uncontrollable parameters must be closely estimated.

Three criteria were examined for use in selecting design parameter values for mechanical harvest systems. A low probability of negative margin (in the range of 10-20%) is proposed as a design criteria because it will provide the highest level of assurance that a proposed harvest system will be of economic benefit.

For convenient use in harvest system design, the relations between the probability of negative margin and various combinations of design parameter values can be described graphically. This procedure is illustrated.

Approved: J B Holtman
Major Professor

Approved: BA Stout
Department Chairman

MECHANICAL HARVEST SYSTEM SIMULATION AND DESIGN CRITERIA FOR PROCESSING APPLES

By

Galen Kent Brown

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1. INTRODUCTION

Apple growers in Michigan are interested in feasible mechanical harvest systems for processing apples. To determine if a mechanical harvest system will be feasible requires knowledge of its economy of operation under the many harvest conditions a grower may encounter. This information could be obtained, after considerable expense and time, by operating actual harvest systems under many conditions. However, a simulation model could provide similar information at less cost and in less time.

This study is intended to define the needed information and develop specific models or procedures so that simulation can be used to evaluate and design mechanical harvest systems for processing apples. The procedures used are expected to be applicable to several other fruit and vegetable crops.

1.1 General Information

A 1968 survey of commercial orchards in Michigan showed nearly 3,450,000 apple trees of which 69% were the standard type and 31% were the semi-dwarf or dwarf type (18). This survey included 55,000 acres of bearing trees with a production of 535,000,000 pounds having a value of

$28,083,000. Over 80% of the Michigan apple industry was located in the western half of the lower penninsula and within about 40 miles of the Lake Michigan shore line.

In 1970 the Michigan Apple Commission had a mailing list of 2000 growers and estimated that 500 of these growers produce 80% of the State's apples.[1] These figures suggest the "average" grower had about 27.5 acres of bearing apple trees while 80% of the production came from farms averaging 88.0 acres of bearing apple trees. Kelsey (14) states: "Commercial fruit production is being concentrated into a relatively small number of farms with larger acreages--standards for a satisfactory income on a tree fruit farm might be 100 acres of bearing fruit--."

During the period 1965-1969, 53-58% of the total apple production in Michigan went into processed utilization (19). Michigan Apple Commission data, Table 1.1, show that more than 50% of the annual production of 6-8 apple varieties went into processed utilization in 1969 and 1970. Formerly, apples were grown and harvested for fresh utilization with the lower quality fruit being graded out for processed utilization. Recently, an increasing number of growers are growing some apple varieties strictly for processed utilization.

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[1]Personal communication, O. D. Pynnonen, Michigan Apple Commission, East Lansing, Michigan, August 31, 1970.

Table 1.1. Michigan Apple Production and Utilization.

Variety	1969			1970		
	Production	Utilization		Production	Utilization	
		Fresh	Processed		Fresh	Processed
	1000 Bu	%	%	1000 Bu	%	%
Summer	344	100	0	324	100	0
Jonathan	4,253	40	60	4,754	45	55
Wealthy	325	38	62	324	35	65
Cortland	275	50	50	291	50	50
Delicious	3,068	75	25	2,319	75	25
Golden Delicious	772	30	70	819	30	70
McIntosh	3,068	40	60	3,644	58	42
Northern Spy	2,331	5	95	2,671	5	95
R. I. Greening	325	0	100	341	0	100
Rome	464	60	40	500	65	35
Stayman	411	50	50	330	60	40
Other	1,507	20	80	1,540	25	75
TOTAL	17,143	40.6	59.4	17,857	44.0	56.0

Michigan Apple Commission, July 30, 1970.

The yearly prices offered by processors for 20 different apple varieties, as published by the Michigan Agricultural Cooperative Marketing Association (4), are not constant from year to year. The price offered depends on many factors, among which are apple production in primary processing states, carryover stocks of processed products, United States disposable income, and processor margin (24, 27).

Apple size as well as quality are important in determining the price received by a grower. Apples must usually be 2½-inch diameter or larger to bring the top price for processing. Apples smaller than this are presently used for juice or cider and bring a price 50-60% less than for the larger size. The grower is not paid for defective apples which result from excessive bruises, punctures, or certain natural defects.

The size of crop varies from year to year depending on weather conditions during the pollination period, size of crop the preceeding year, and other factors.

Weather conditions during the harvest season can have a major affect on the quantity and quality of the crop, and can be expected to be different for each major apple growing area in the state. Windstorms during harvest may cause a large portion of the crop to become windfalls, which usually have very low value. Water supply (rain) during the harvest season can affect the growth rate of apples, and thus the total yield and size distribution of the crop. Rain also results in lost work time and thus affects the harvest rate--acreage relation for any harvest method.

1.2 Need for Harvest Mechanization

The number of workers on Michigan farms decreased at an average annual rate of 5.5% during 1955-65 (28). Many fruit growers have difficulty obtaining enough pickers to harvest their fruit at the proper time.

Hired labor is recognized as a major item of cost in fruit production and is often greater than 50% of the total cost of production (29). There is, however, a wide difference between a worker's average hourly earnings in agriculture and in manufacturing. If harvesting was mechanized, increased productivity might permit hourly wages to be increased and would reduce the peak demand for harvest labor.

The trend toward growing more apples strictly for processed utilization, the need to increase worker productivity, and a need to increase grower income all reinforce the interest in mechanical harvest methods for apples. Several state and federal research agencies in the United States are now working on the development of mechanical harvest methods for apples, as well as apricots, avocados, cherries, peaches, pears, oranges, grapefruit, lemons, and papaya.

1.3 Need for a Simulation Model

Analytical techniques for estimating the necessary or allowable values for mechanical harvester performance parameters have been proposed and used for prunes, apricots and cling peaches (9), citrus (5, 13, 33), apples (30), and various fruits and vegetables (10). All of these techniques have used average values for the variables, with the performance parameters computed for a breakeven condition (based on harvest costs or grower returns) between the conventional hand harvest method and a proposed mechanical harvest method.

A stochastic simulation model for evaluating the effect of harvest policy, labor cost, fruit sale price, and fruit ripening rate on expected net return to papaya growers was developed by Wang, et al. (32). Such a model has not been developed for apple growers, although many of the variables in apple production, harvesting, and marketing are of a stochastic nature. A simulation model is needed for evaluating conceivable mechanical harvest systems and specifying the necessary values for many of the design parameters. Such a model will provide valuable information not presently available to researchers, designers, growers, and processors.

1.4 Objectives of the Study

As an initial step toward meeting the above need, the following objectives were selected.

1. Design a harvest simulation model which can be used to evaluate the economic benefit of mechanical harvest systems for an apple grower whose production is strictly for process utilization.
2. Design the necessary sub-parts of the above simulation model which are required to describe yields, important weather occurrances during harvest (wind, lost time due to rain), and harvest rate--acreage relationships.
3. Define outputs from the simulation model which provide planning information not presently available to researchers, designers, growers, and processors.
4. Evaluate a hypothetical mechanical harvest system, for illustration purposes, using available information and the simulation model.
5. Develop a technique for specifying the needed values of the harvest system design parameters so that the risk of negative margin for a mechanical harvest method compared to the hand harvest method is at a particular probability level. Margin = [(income from mechanically harvested crop - mechanical harvest cost) - (income from hand harvested crop - hand harvest cost)].

2. FORMULATION OF THE SIMULATION MODEL

The objectives of this study are stated in general terms at the end of Chapter 1. Formulation of the simulation model to meet these objectives involved consideration of both the type of outputs desired and the type of inputs available.

Simulation models can be formulated in either the continuous time form (described by differential equations) or the discrete time form (described by difference equations). The choice of a continuous or a discrete time model depends upon: (1) the level of detail necessary to answer relevant questions; (2) the frequency of events or the flow rate of objects relative to the minimum time interval of interest; and (3) the cost of programming and operating the models (17). The outputs (defined in Section 2.4) are intended to provide both annual and planning period (i.e., the period of years required to payoff the machine investment) information. Some input information is available on a daily basis and some is available on an annual basis. After considering all of these facts, the discrete time form was selected with a simulation time increment of one day.

Accurate output information requires both accurate input data and the use of accurate functional relations in the model. Annual input data on fruit quality, fruit value, labor costs, and equipment costs are available from historical records, as are daily input data on weather conditions. Known functional relations between yields, harvest cost, and crop income were used to insure realism in the economic behavior of the model.

To include all possible interactions and inputs in the model formulation, a very complex mathematical model would be required. In general, the mathematical model should be formulated to yield reasonably accurate descriptions or predictions of the behavior of a given system while minimizing computational and programming time (22). Thus, boundaries were imposed on the scope of the defined problem. Factors such as: costs not incurred in the harvest operation; management ability of the grower; losses due to labor shortages, strikes, or carelessness; and alternate investment strategies were not included in the model formulation. These types of cost factors are difficult to quantify and, in the opinion of the author, are not required for the relative evaluation of mechanical harvest systems.

The many variables, parameters, outputs, and other factors of importance in the mathematical model were grouped as suggested by Asimow (1). These groups are discussed in the following six Sections.

2.1 Controllable Inputs

These inputs were assumed to be controllable by the equipment designer, the equipment operator, or both.

ECOST - Initial equipment costs, dollars

ELIFE - Equipment life, years

OPER - Crew size, number of workers

HRATE - Harvest rate, trees per hour

RH - Machine recovery, portion of on-tree yield

RP - Pickup recovery, portion of on-ground yield

HI - Fruit injury, portion of harvested volume

2.2 Uncontrollable Inputs

These inputs were assumed to be uncontrollable by the equipment designer, operator, or both.

NVAR - Number of varieties considered

ACRES - Acres of producing trees for each variety

TREED - Tree density, trees per acre

TII - Taxes, insurance, interest, expressed as a fixed proportion of initial equipment cost

RFO - Cost of repairs, fuel, taxes, dollars per hour

TRCOST - Tractor cost, dollars per hour

2.3 Environmental Inputs

These inputs were assumed to be solely the result of climatic or economic conditions not highly controllable by the grower.

Y_o - Initial on-tree yield, bushels per tree

Y_i - On-tree yield, day i, bushels per tree

YW_i - On-ground (windfall) yield, day i, bushels per tree

WL_i - Windloss for day i, portion of on-tree yield

GR - Growth rate, daily increase in on-tree yield

PG - Portion of the crop 2½-inch diameter and larger

DNAT - Portion of the crop with natural defects

ROT - Portion of windfall fruit which is decayed

PRICE - Dollars per hundredweight (cwt) for fruit of processing, juice, or drop quality

OCOST - Labor cost, dollars per man-hour for mechanical harvest

PCOST - Handpicking cost, dollars per bushel

2.4 Model Outputs

The following outputs were considered to be sufficient to provide the necessary information required to meet the objectives of the study.

YMAR - Margin, dollar difference per year between mechanical harvesting and hand harvesting

EMAR - Expected value of YMAR

SDMAR - Standard deviation of YMAR

PMAR - Planning margin, sum of YMAR during the planning period

EPMAR - Expected value of PMAR

SDPMAR - Standard deviation of PMAR

HC - Harvest cost, dollars per bushel

EHC - Expected value of HC

SDHC - Standard deviation of HC

PROD - Productivity, bushels mechanically harvested per man-hour

EPROD - Expected value of PROD

SDPROD - Standard deviation of PROD

PR - Ratio of processing volume for mechanical harvest compared to hand harvest

EPR - Expected value for PR

SDPR - Standard deviation of PR

JR, EJR, SDJR - Ratio, expected value, and standard deviation for juice volume

DR, EDR, SDDR - Ratio, expected value, and standard deviation for windfall volume

The probability of negative margin can be calculated from EYMAR, SDYMAR, and the probability density function (pdf) for YMAR. A similar procedure can be used for calculating the probability of negative planning margin.

2.5 Design Parameters

The researcher, faced with the problem of evaluating various methods for mechanically harvesting apples, must determine acceptable values for all of the Controllable Inputs, listed in Section 2.1, considering the constraints placed on all parameters in the system. For this reason all of the Controllable Inputs in this study are considered to be design parameters.

Other factors, not explicitly stated here, can also be considered as design parameters due to their direct influence on some of the Controllable Inputs. Examples of such factors would be: tree modification to decrease fruit injury, increase fruit removal, and increase harvest rate; the use of special chemicals to reduce wind losses, increase fruit removal, or decrease fruit decay; and shared use of harvest equipment with other crops such as cherries, peaches, pears, and plums so that the relative equipment cost can be reduced. However, because such factors are still experimental or require particular conditions they will not be analyzed in this study.

2.6 Criteria for Measuring Goodness

Establishing exact goodness criteria is a difficult task which will certainly result in different criteria if left to the various interest groups involved. However, general guidelines suggest that the following conditions should exist:

1. The probability of negative margin and planning margin should be low.
2. Worker productivity should be high enough so that labor requirements for harvest are compatible with year-around requirements and worker hourly earnings are comparable to those in manufacturing.
3. The expected volumes of fruit in various quality categories should be within manageable limits for the grower and processor.

2.7 Mathematical Relations in the Model

The volume of fruit available for harvesting from each tree is determined for the first day of harvest and is then adjusted daily to reflect the effects of windfalls and fruit growth, according to the recursive relations:

$$Y_1 = Y_0 \ (1 - WL_1)$$

$$Y_2 = Y_1 \ (GR)(1 - WL_2)$$

$$Y_{i+1} = Y_i \ (GR)(1 - WL_{i+1})$$

The accumulative volume of fruit available for harvesting from the ground at each tree as windfalls is determined by the relations:

$$YW_1 = Y_0 \ (WL_1)$$

$$YW_2 = Y_1 \ (GR)(WL_2) + YW_1$$

$$YW_{i+1} = Y_i \ (GR)(WL_{i+1}) + YW_i$$

The volume of fruit harvested from the tree or picked up from the ground is determined with the following two equations:

$$\text{Volume from tree} = Y_i \ (RH)$$

$$\text{Volume from ground} = YW_i (1-ROT) \ RP$$

The volume equations are multiplied by the number of trees harvested each day, then summed daily to determine total volume for each season. The number of trees harvested each day is determined with the following equation:

$$\text{Trees harvested} = HRATE \times HT$$

Harvest time, HT, is determined daily and depends upon the occurrence of a Sunday, lost time due to rain, or a mechanical breakdown.

Hand harvest cost for picking fruit, or picking up fruit, is calculated by converting the volumes to hundredweight (cwt), then multiplying by the appropriate picking cost.

Mechanical harvest cost is calculated using the following relation:

$$\text{Annual mechanical harvest cost} = ECOST \left(\frac{0.90}{ELIFE} + \frac{TII}{2}\right)$$

$$+ (RFO + TRCOST + OPER \times OCOST) \ HTIME$$

This relation assumes straight-line depreciation, a salvage value of 10% of the initial equipment cost, and that maintenance and operating costs are directly proportional to the annual hours of operation (HTIME). HTIME is accumulated for each harvest method as the simulation proceeds through each season.

Three categories of fruit are assumed to have economic value. The volume of fruit per tree in each category is determined with the following three equations:

$$\text{Processing} = Y_i(\text{PG-DNAT})(1\text{-HI})\ \text{RH}$$

$$\text{Juice} = Y_i[(1\text{-PG}) - \text{DNAT}]\ (1\text{-HI})\ \text{RH}$$

$$\text{Windfall} = YW_i\ (1\text{-ROT})\ \text{RP}$$

The grower is paid processing prices for fruit which is 2½-inch diameter or larger and is not a windfall, unless it has natural defects or excessive harvest injury.

The grower is paid juice prices for fruit which is less than 2½-inch diameter and is not a windfall, unless it has natural defects or excessive harvest injury.

All fruit picked up from the ground are classed as windfalls regardless of size or natural defects. If a market exists for this category of fruit, the grower is paid windfall prices for fruit which does not have decay or excessive harvest injury.

Income is calculated by converting the total volume in each category to cwt, then multiplying by fruit value and summing over each category.

After completion of each season, the difference between income and cost is computed for each harvest method, then the difference for hand harvesting is subtracted from the difference for mechanical harvesting to determine margin. The expected value and standard deviation of margin is computed for each year as is the expected value and standard deviation of planning margin. These statistics can be used to calculate the probability of negative margin and negative planning margin.

2.8 Assumed Grower Characteristics

Michigan apple processors buy at least 20 apple varieties and a typical Michigan grower may raise several of these. For purposes of this simulation, the four varieties with the largest processed volume (McIntosh, Jonathan, Golden Delicious, Northern Spy) were assumed to be a representative cross-section of the varieties used for processing. In addition, a typical proportion of total acreage was estimated for each variety using tree population data published in the 1968 survey (18), and average tree planting densities for standard type trees. This information is summarized in Table 2.1.

2.9 Stochastic Simulators Required

Many of the Environmental Inputs are of a stochastic nature. However, some are more important than others in terms of their expected variations and affect

Table 2.1 Determination of Acreage Proportions.

Variety	Number[1]	Trees/Acre[2]	Acres[3]	% Acres
McIntosh	279,053	27	10,340	25
Jonathan	650,350	34	19,130	45
Golden Delicious	177,400	34	5,220	13
Northern Spy	193,308	27	7,160	17
TOTALS			41,900	100

[1]Number of trees in Michigan. Taken from Table 7, Michigan 1968 Fruit Tree Survey.

[2]Estimate of typical planting density for standard type trees, obtained from Frank Klackle, District Extension Horticultural Agent, Grand Rapids.

[3]Calculated from number of trees and typical planting density.

on the outputs. For this simulation, initial annual yield, daily windloss, daily work time lost due to rain or the occurrence of Sundays, and the occurrence of a breakdown of the mechanical harvester were modeled as stochastic processes. The design of each model is discussed in detail in a following chapter.

3. YIELD SIMULATOR

Annual yields for all apple varieties vary from year to year. Hoblyn, *et al.* (12) studied the fruiting habits of 15 varieties of apple in England. They proposed two constants, B and I, which could be calculated from yield records to describe the biennial bearing tendency. The constant B (on a scale from zero to 100) indicates whether the variety is wholly, partially, or not at all biennial. The constant I (on a scale from zero to 1.0) indicates the magnitude of the yield fluctuations. Their study showed B values from 61 to 91 and I values from 0.26 to 0.71, with grand means of 74.3 and 0.48 respectively, for 12 years of data on the 15 varieties. Wilcox (34) conducted a study of correlations between tree growth and fruiting and found that fruit set (thus yield) one year had a highly significant negative correlation with set (thus yield) the following year. Singh (25) reported that alternate bearing of certain fruit plants (including apple) is a major problem in commercial fruit growing all over the world. He listed 125 references relating to some aspect of the alternate bearing problem.

Annual apple yields are recognized to be stochastic in nature, alternating from high to low depending on the variety and geographic location of the planting.

3.1 Available Data

Accurate records of total annual yield (volume picked + volume windfall) by variety are not maintained by most growers. Instead, the grower has a mental record, or impression, of what his minimum, most likely (typical), and maximum annual yield has been for each variety. Based on replys from five growers and horticultural agents, values for the above classes of yield were determined, Table 3.1.

Yield records for a typical planting of the four apple varieties were obtained from the Graham Experimental Station at Grand Rapids, Table 3.2. Using these data to determine means and standard deviations would not be statistically desirable because the data covers a short time period and this planting was only one of many similar plantings in the Grand Rapids area. However, these data were used to: (1) calculate biennial bearing tendency; B, and intensity, I: (2) estimate the correlation between successive annual yields; and (3) estimate the relative size of the standard deviation of annual yield for each variety.

Table 3.1. Estimated Annual Yields.

Variety	Annual Yield,[1] bushels per tree			Trees Per Acre	Annual Yield, bushels per acre		
	Minimum	Most Likely	Maximum		Minimum	Most Likely	Maximum
McIntosh	5	20	25	27	135	540	675
Jonathan	4	15	20	34	136	510	680
Golden Delicious	4	15	20	34	136	510	680
Northern Spy	0	20	25	27	0	540	675

[1] Based on grower and horticultural agent opinion of annual yields (volume picked + volume windfalls) for a commercial grower.

Table 3.2. Annual Yield Data.

Year	Annual Yield,[1] pounds per tree			
	McIntosh	Jonathan	Golden Delicious	Northern Spy
1948	0	0	1	0
1949	4	15	9	0
1950	50	40	40	0
1951	87	72	91	2
1952	142	132	65	2
1953	184	86	119	38
1954	259	133	76	58
1955	121	91	347	296
1956	514	277	146	78
1957	176	248	556	291
1958	650	305	125	292
1959	407	565	630	504
1960	1126	508	217	284
1961	1170	709	866	1112
1962	699	602	349	19
1963	926	538	965	695
1964	1158	766	381	504
1965	443	439	979	880
1966	1086	625	168	126
1967	398	430	947	658
1968	823	879	531	358
1969	1112	566	943	1044
1970	830	994	386	468

[1]Average for Hibernal and Seedling interstocks, Block 2, Graham Experimental Station, Grand Rapids, Michigan.

3.2 Model Formulation

For harvest simulation, a time series of either historical yields or stochastically generated yields is required. Historical records have the disadvantages of limited length and number. For these reasons a stochastic model was developed for generating an annual yield time series.

The Graham Station yield data were plotted and the first year of commercial production was estimated. Commercial production is characterized by fairly level production over a period of years. The biennial bearing tendency and intensity, Table 3.3, were calculated using yield data for the first and succeeding years of commercial production. The results show that during the 9-12 years of commercial production, the biennial bearing tendency was very strong in McIntosh and Jonathan and complete in Golden Delicious and Northern Spy. The intensity was between 0.27 and 0.55 for all varieties.

Yield each year is an integrated result of many factors some of which may be tree age, tree surface area, variety, nutrition, water supply, frost at pollination time, amount of hand or chemical thinning, and yield the previous year. For the purpose of constructing a usable yield simulator, it was hypothesized that successive yields during commercial production (no growth trend present) could be described by the first-order lag model:

Table 3.3. Biennial Bearing Statistics.

Variety	Years[1]	B^2	I^3	$\hat{\rho}^4$	ρ^5
McIntosh	1959-70	70	0.27	-0.45	-0.45
Jonathan	1961-70	88	0.34	-0.60	-0.55
Golden Delicious	1962-70	100	0.47	-0.93	-0.80
Northern Spy	1961-70	100	0.55	-0.77	-0.70

[1]Years representative of commercial production, Table 3.2.

[2]Biennial bearing tendency =

$$\frac{\text{Number of pairs of years with sign of } (Y_{i+1} - Y_i) \text{ different}}{\text{Total number of pairs of years}}$$

[3]Biennial bearing intensity = Average of $\frac{|Y_{i+1} - Y_i|}{Y_{i+1} + Y_i}$

[4]Estimate of the correlation between annual yields Y_i and Y_{i-1}, after adjusting for any growth trend present in the data.

[5]Assumed correlation between Y_i and Y_{i-1}, used in the autoregressive yield model.

$$Y_i = \mu + \rho\ (Y_{i-1} - \mu) + e_i$$

Where:

Y_i = Annual yield, year i

Y_{i-1} = Annual yield, year i-1

μ = Mean annual yield

ρ = Correlation between Y_i and Y_{i-1}

e_i = Random disturbance term, year i

A slight growth trend is suggested in the commercial production yield data for all varieties, Table 3.2, so perhaps production had not yet leveled off for these trees. Prior to estimation of ρ, the linear time trend was removed by regressing Y_i on time using the model:

$$Y_i = \alpha + \beta t_i + v_i$$

Where

Y_i = Annual yield, year i

t_i = Year number corresponding to Y_i

α = Y_i intercept at t_o

β = Slope relation between Y_i and t_i

v_i = Random disturbance term, year i

Residuals from this model were calculated for each Y_i, then ρ was estimated by the product-moment method (26):

$$\hat{\rho} \quad \frac{\sum_{i=2}^{n} r_i \, r_{i-1}}{\sqrt{\sum_{i=2}^{n} r_i^2} \sqrt{\sum_{i=2}^{n} r_{i-1}^2}}$$

Where:

$\hat{\rho}$ = Estimate of correlation between Y_i and Y_{i-1}

r_i = Residual for Y_i, from linear time trend model

r_{i-1} = Residual for Y_{i-1}, from linear time trend model

n = Number of residuals available

The results, Table 3.3, show that all correlations are negative. A statistical test of the null hypothesis H_o: $\rho = 0$ against the alternative hypothesis H_1: $\rho < 0$ cannot be applied to these coefficients because their distribution is not known. Furthermore, the basic assumption in correlation analysis of independence between successive dependent variables has been violated by the hypothesized first-order lag model.

The correlations were calculated from one set of data covering a relatively short time, and thus could be inaccurate estimates of the true correlations. Grower opinion suggests that the relative order of correlation magnitudes among varieties should be as calculated.

To represent the correlation between successive annual yields for a commercial size grower, and mature trees, the ρ values shown in Table 3.3 were assumed. These are somewhat subjective, but are thought to be reasonable.

To generate random yields having a specified mean, standard deviation, and correlation between successive values, as hypothesized in the first-order lag model, an equivalent first-order autoregression model described by Llewellyn (16) was used. The general yield model for each variety is given by:

$$Y_i = \mu + \rho\ (Y_{i-1} - \mu) + \sigma\ (1 - \rho^2)^{\frac{1}{2}}\ X_i$$

Where

Y_i = Correlated annual yield per tree, year i

Y_{i-1} = Correlated annual yield per tree, year i-1

ρ = Correlation between Y_i and Y_{i-1}

μ = Mean of Y_i

σ = Standard deviation of Y_i

X_i = Standardized random variable calculated from:

$$X = \left(\frac{Y-\mu}{\sigma}\right)$$

Where: Y = Random (uncorrelated) value for annual yield generated from the cummulative distribution function (CDF) for annual yield

μ, σ = Same as above

The random disturbance term, e_i, in the first-order lag model corresponds to the $\sigma(1 - \rho^2)^{\frac{1}{2}}\ X_i$ term in the autoregression model.

The parameters μ and σ and the CDF need to be specified before the autoregression model can be used.

3.3 Parameter Estimation

Estimates of the parameters μ and σ were calculated using assumed yield pdf's based on the estimated minimum, most likely, and maximum annual yields, Table 3.1. The final pdf's selected, and corresponding estimates for μ and σ, are given in Figure 3.1 and Table 3.5. The mean yields

Table 3.4. Statistics for Annual Yield Data.

	Time Period[1]	Mean[2]	Standard Deviation[2]
McIntosh	1959-1970	20.2	7.14
Jonathan	1961-1970	15.6	4.36
Golden Delicious	1962-1970	15.0	7.78
Northern Spy	1961-1970	14.0	8.67

[1]Years representative of commercial production, Table 3.2.

[2]Bushels per tree.

Table 3.5. Statistics for Assumed Yield pdf's.

	Yield per Tree[1]		Yield per Acre	
	Mean	Standard Deviation	Mean	Standard Deviation
McIntosh	17.16	4.41	463	119
Jonathan	14.12	3.04	480	103
Golden Delicious	13.47	3.63	458	123
Northern Spy	14.19	5.55	383	150

[1]Bushels per tree assumed for the yield models.

for the assumed pdf's are somewhat less than for mature trees at the Graham Station, Table 3.4, but are felt to be more representative of a long-time average. Kelsey, Harsh, and Belter (15) state that a yield of 400 bushels per acre (all varieties) would be a representative average for an above average apple grower. The mean yields for the pdf's are 16-20% above that average, except for Northern Spy, because processed utilization is assumed and windfalls are initially included in annual yield generated from the pdf's. Mean yield for the Northern Spy pdf is less than 400 bushels per acre because this variety can have nearly zero yield some years, and has below average yield for many growers.

The standard deviations for the assumed pdf's are less than for the Graham Station data. The Station data represent a small sample and thus could be unrepresentative. However, the relative magnitude of the pdf standard deviations are in the same order as for the Station data and are felt to be realistic based on grower opinion of yield variation.

The pdf's were assumed to be composed of straight lines because: (1) adequate observations of annual yield are not available which allow plotting of yield histograms and selection of a statistically rigorous shape; (2) assuming a quasi-beta shape (a cosine curve from the minimum to most likely and from most likely to maximum values) for the pdf's resulted in a small standard deviation; and (3) the straight-line pdf's can be easily altered to change mean and standard deviation values.

Each assumed pdf was integrated to obtain the CDF of yield. The random annual yields, Y, required in the autoregression model are calculated via inverse transforms of uniform (0, 1) random numbers generated using a multiplicative congruential technique (22).

3.4 Yield Model Characteristics

Llewellyn (16) has described the task of determining the true mean, variance, correlation coefficients of the stochastic process, and distribution of the underlying independent sequence, such as assumed in the first-order lag model, as impossible. Thus, when generating a series of autoregressive events it is advisable to be aware of the pdf of the sequence being formed.

To estimate differences between the yield distributions based on minimum, most likely, and maximum values and those formed by the autoregression model, computer runs were made in which 5000 yield observations were generated, and histograms were developed. The "grower" distributions and "model" distributions are shown in Figure 3.1. The mean and standard deviation values are almost equal but the distribution shapes become progressively different as the amount of negative correlation is increased. This

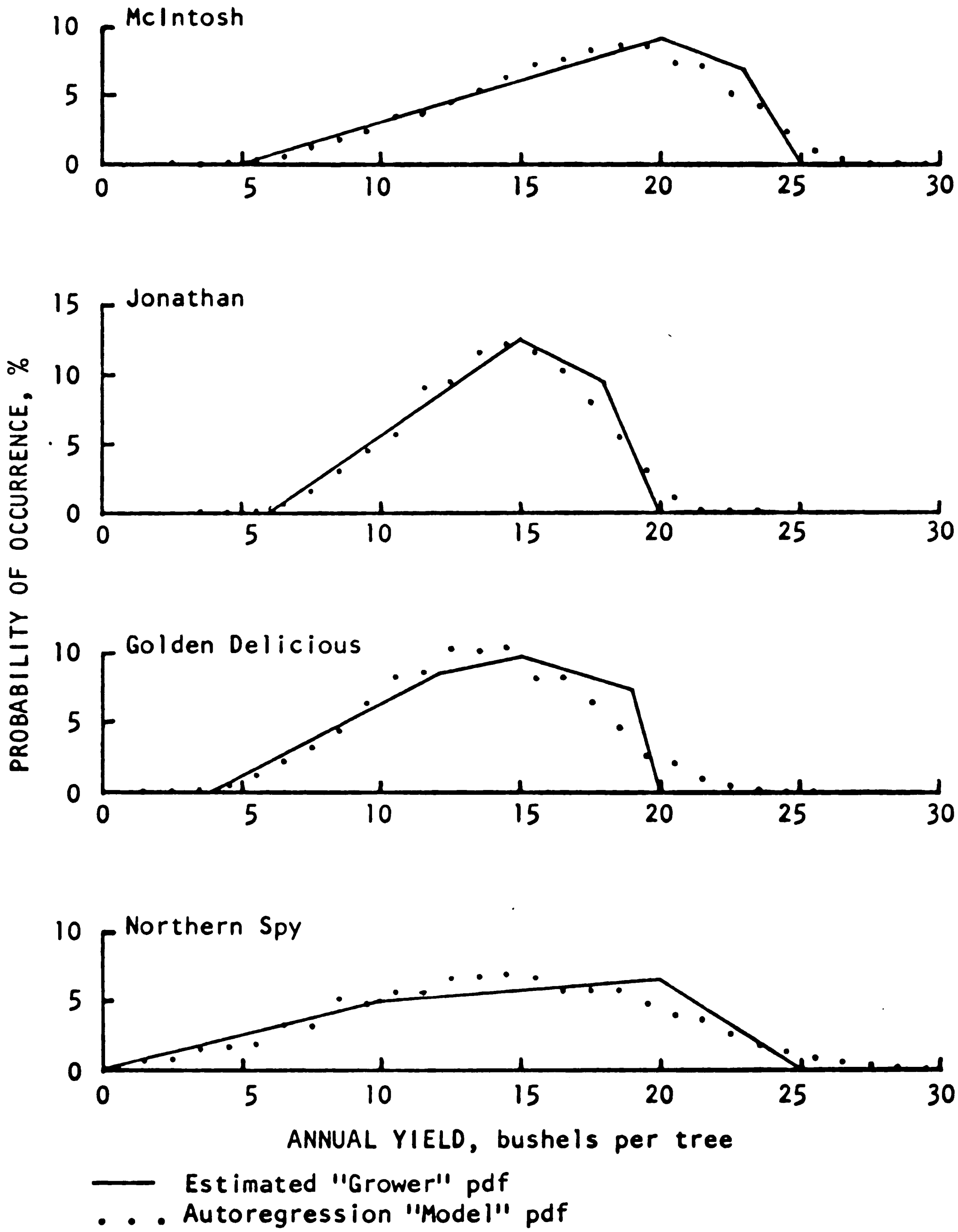

Figure 3.1 Annual Yield pdf's.

result is logical because if the correlation was -1.0 successive yeilds would have to be equidistant above and below the mean. Thus, a symmetric distribution would result.

3.5 Daily Fruit Growth

Fruit continue to grow after reaching the earliest stage of maturity at which a grower can begin harvest. To evaluate the change in yield per tree due to fruit growth a value for daily growth rate during the harvest period is needed. Growth rate will vary with variety and water supply.

3.5.1 Available Data

Estimated optimum harvest dates for long-term storage of McIntosh, Jonathan, and Red Delicious apples are now published each year for Michigan (6). Data on fruit weight before and during harvest, including the random effect of water supply, are gathered from selected orchards at weekly intervals for use in that study. From these data, weekly weight for one sample of 20 apples at each of four orchards in the Grand Rapids area were obtained for the McIntosh and Jonathan varieties for the years 1969-1970 and 1968-1970 respectively. A daily growth rate was computed for each orchard and weekly interval using the relation:

$$GR = \sqrt[7]{W_8/W_1}$$

Where:

GR = daily growth rate

W_8 = observed weight on day 8

W_1 = observed weight on day 1

This relation was derived from the recursive relation:

$$W_2 = (GR)\ W_1$$
$$W_3 = (GR)\ W_2 = (GR)^2\ W_1$$
$$\vdots \qquad \vdots$$
$$W_8 = (GR)^7\ W_1$$

The mean and standard deviation of GR, calculated for all observations on each variety, are given in Table 3.6.

Table 3.6. Growth Rate Statistics.

Variety	Mean	Standard Deviation
McIntosh	1.0081	0.0115
Jonathan	1.0044	0.0074

Similar data were not available for the Golden Delicious and Northern Spy varieties, so the statistics for McIntosh were assumed to apply to both varieties. This assumption was made because the three varieties have similar size apples. Growth rate will have a minor influence on the results of the harvest simulation, but is required in order to evaluate the effect of delayed harvest policies on harvested volume, and windloss.

After the crop is judged mature the volume of fruit per tree available for harvesting can be adjusted daily using the relation given in Section 2.7. For this study the change in on-tree yield is assumed to be directly proportional to the change in weight. The mean value for growth rate, Table 3.6, will be used instead of a randomly generated value.

4. WINDFALL SIMULATOR

The percentage of yield classed as windfalls, hereafter referred to as windloss, varies from year to year. Hormone (stop-drop) sprays are available which may be applied to the trees prior to harvest to reduce the expected amount of windloss (3). Such sprays, containing Alpha-naphthalenacetic acid (NAA) or 2,4,5-trichlorophenoxypropionic acid (2,4,5-TP), have been used for many years by most Michigan apple growers. A new material, succinic acid-2,2-dimethylhydrazide (SADH or ALAR^{R}), is becoming increasingly popular for certain varieties because among other desired effects, it is an effective stop-drop and delays maturity by 7-10 days. However, it is not clear if apples sprayed with this material will adequately loosen for mechanical harvesting. In developing this simulator, the proper use of a conventional stop-drop spray has been assumed.

Annual windloss is the integrated result of variety, wind occurrences, and the number of days required to complete the harvest. To adequately simulate the windloss process a stochastic model is needed for daily wind velocity, the length of harvest period must be defined, and a relationship between daily wind velocity and daily windloss must be developed.

4.1 Available Data

Accurate records of annual windloss are not maintained by most growers and although a literature search provided some data, no long time records were found from which a pdf for windloss could be constructed. Also, no data were found relating daily wind velocity and daily windloss.

Grower and Horticultural Agent opinion were used to estimate the mean, maximum, and minimum annual windloss. They thought that windloss for the McIntosh variety should be about twice that for the other three varieties. In addition, some impression about the shape of the annual windloss pdf was provided by estimates of the number of times annual windloss within specified intervals has occurred during the past 20 years. These estimates are given in Table 4.1.

Daily records for wind occurrences in the Grand Rapids area are available from the U.S. Weather Bureau. It was hypothesized that both magnitude and duration of wind are important in determining the daily windloss. For this reason the daily "Average Speed" (8), hereafter referred to as daily average velocity, was selected for use in the daily windloss model.

After reviewing the work of Murneek (21), Batjer and Marth (2), Thompson and Batjer (31), and Edgerton and Hoffman (7), the minimum daily windloss for McIntosh was

Table 4.1. Estimated Annual Windloss pdf's.

McIntosh

Annual Windloss[1]	0-10%	10-20%	20-30%	30-40%	Over 40%
Probability	0.45	0.40	0.10	0.05	0.0

Jonathan, Golden Delicious, Northern Spy

Annual Windloss[2]	0-5%	5-10%	10-15%	15-20%	Over 20%
Probability	0.45	0.40	0.10	0.05	0.0

[1]Expected value is 10-12%.

[2]Expected value is 5-6%.

assumed to be 0.2% and for the other varieties 0.1%. Daily windloss greater than this was assumed to be the result of daily average wind velocity greater than some unknown base.

The nominal length of harvest period for each variety was provided by individuals with considerable experience in the apple industry, Table 4.2.

4.2 Model Formulation

The pdf for daily average velocity was constructed for the period September 7-October 30 of 1951 and 1953-1970 at the Kent County Airport in Grand Rapids, Figure 4.1. The means and standard deviations were calculated for every

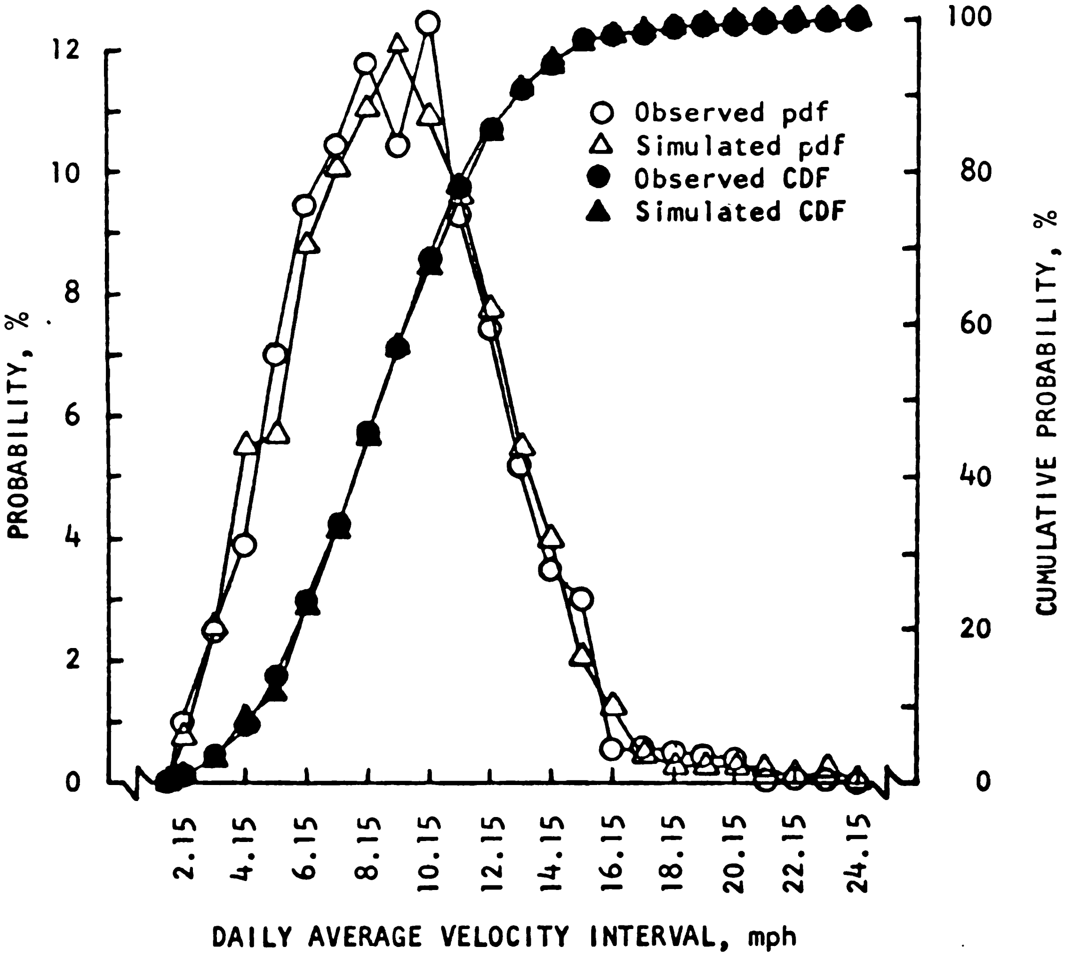

Figure 4.1 Daily Average Wind Velocity pdf's and CDF's.

Table 4.2. Length of Harvest Period.

Variety	Days of Harvest
McIntosh	10
Jonathan	14
Golden Delicious	10
Northern Spy	10

day of the period. From these results, and the fact that this is a relatively short period, it was hypothesized that the mean and standard deviation of daily average velocity could be assumed constant over the period. Furthermore, using the method discussed in Section 3.2, the correlation between velocities on successive days was estimated at 0.36.

For the purpose of constructing a wind velocity simulator it was hypothesized that successive velocities could be described by the same first-order lag model as discussed in Section 3.2. Random velocities having a specified mean, standard deviation, and correlation between successive values were generated using the autoregression model (16):

$$WV_i = \mu + \rho\ (WV_{i-1} - \mu) + \sigma\ (1 - \rho^2)^{\frac{1}{2}}\ X_i$$

Where:

WV_i = Correlated average velocity, day i

WV_{i-1} = Correlated average velocity, day i-1

ρ = Correlation between WV_i and WV_{i-1}

μ = Mean of WV_i

σ = Standard deviation of WV_i

X_i = Standardized random variable calculated from:

$$X = \left(\frac{Y-\mu}{\sigma}\right)$$

Where: Y = Random (uncorrelated) value for velocity generated from the CDF for daily average velocity

μ,σ = Same as above

The model for daily windloss was assumed to be of the form:

$$WL_i - CON \qquad , WV_i < WVB$$
$$WL_i = CON + D\ (WV_i - WVB)^n, WV_i \geq WVB$$

Where:

WL_i = Windloss for day i

WV_i = Daily average velocity, day i

WVB = Base daily average velocity

CON = Minimum daily windloss (0.002 for McIntosh, 0.001 otherwise)

D = Slope parameter

n = Exponent

The annual windloss was assumed to be the ratio of total volume of windfalls to total volume harvested plus windfalls. The parameters D, WVB, and n in the daily windloss model were not available from data, but were determined using an iterative procedure requiring that the expected value and pdf for annual windloss, Table 4.1, be closely matched. This procedure is discussed in the next Section.

Table 4.3. Wind Velocity Model Parameters.

μ	σ	ρ
9.12 mph	3.26 mph	0.36 mph

4.3 Parameter Estimation

Table 4.3 gives the grand mean and standard deviation (calculated using residuals from the grand mean for all observations) for daily average velocity, and the estimated correlation between successive velocities. The estimated correlation is based on about 1000 observations and was assumed to be the correct value. While the residuals of velocity may be normally distributed, a significance test of the estimated correlation was not performed because the necessary condition of independence between successive velocity observations is violated by the hypothesized first-order lag model.

The pdf for velocity was integrated to obtain the CDF for use in generating Y, the random velocity values.

An iterative program was written for use in estimeting the parameters D, WVB, and n. This program used the annual yield model, wind velocity model, daily windloss model, lost work time model (discussed in Section 5.2), and length of harvest period to generate annual windloss observations for a specific variety over a period of NY years. The mean and standard deviation of annual windloss were calculated and the observations were sorted into a pdf having the same loss intervals as the assumed pdf's given in Table 4.1.

Preliminary runs were made using exponents, n, of 1, 2, and 3 each with 16 combinations of D and WVB, covering a narrower range, until the estimated and simulated pdf's and expected values for annual windloss were in close agreement, based on 800 years of simulated observations. The values of D and WVB giving best agreement were used for all subsequent windloss modeling, and are listed in Table 4.4 along with the expected value, and its standard deviation, of annual windloss.

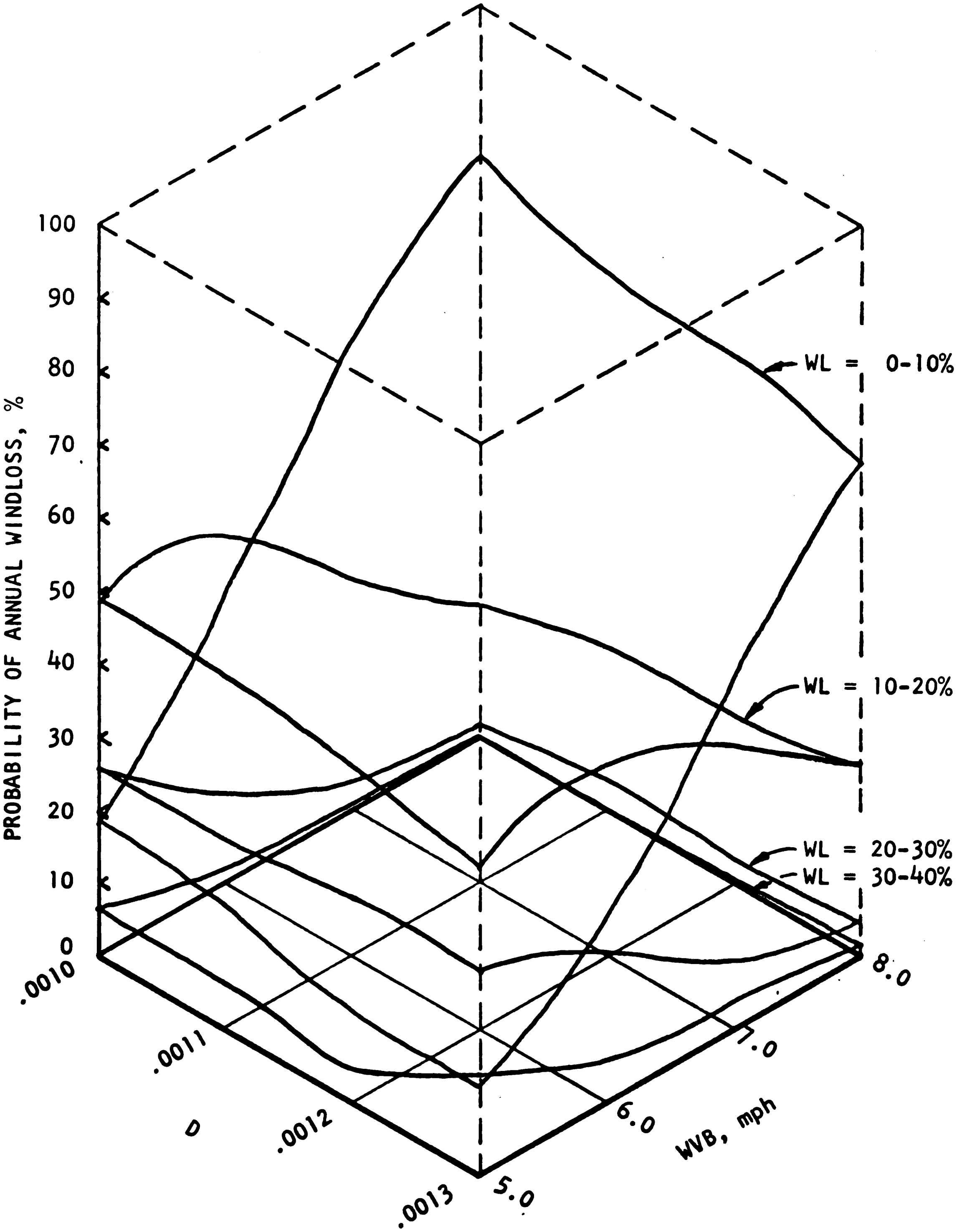

Figure 4.2 Response Surface for McIntosh Windloss.

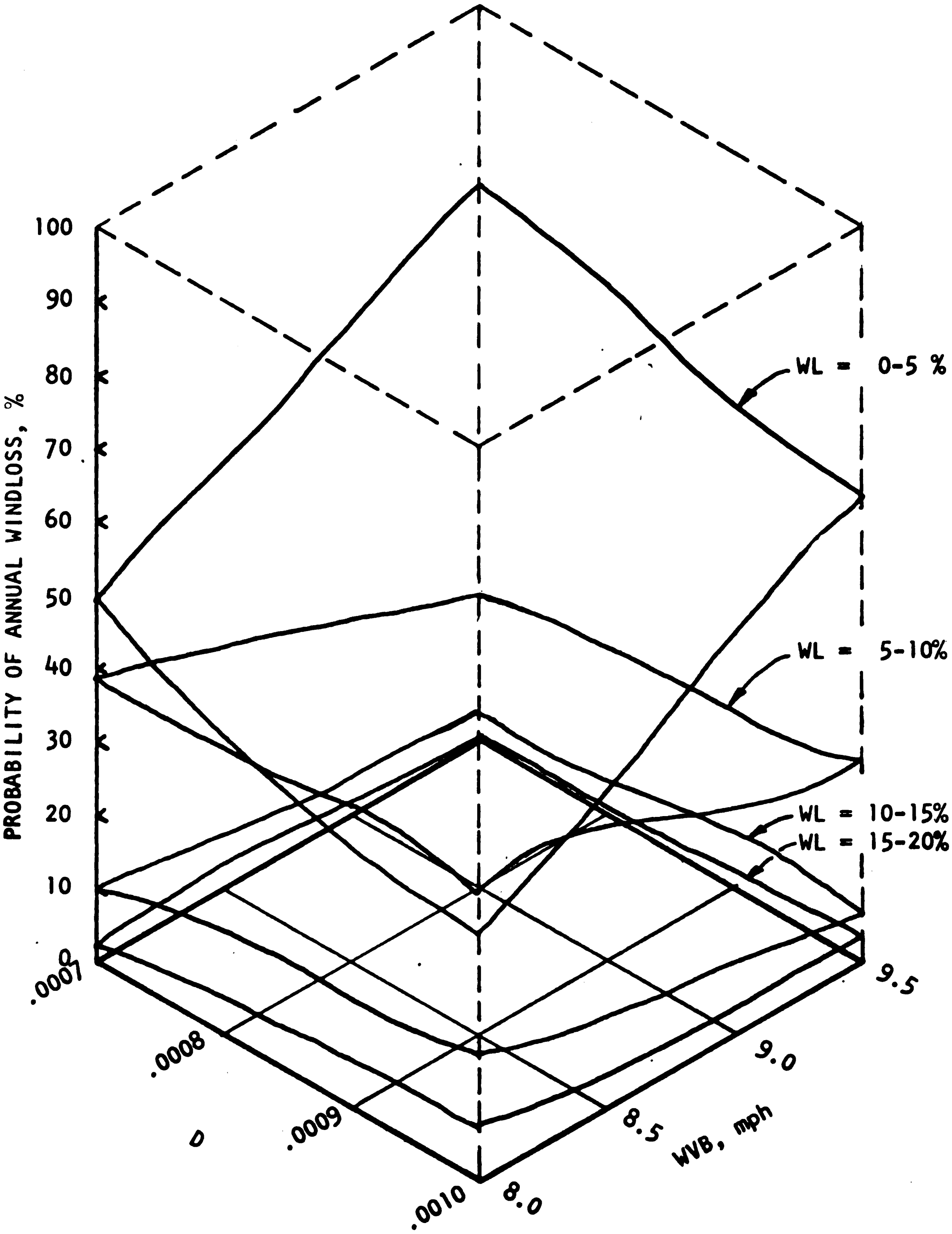

Figure 4.3 Response Surface for Jonathan Windloss.

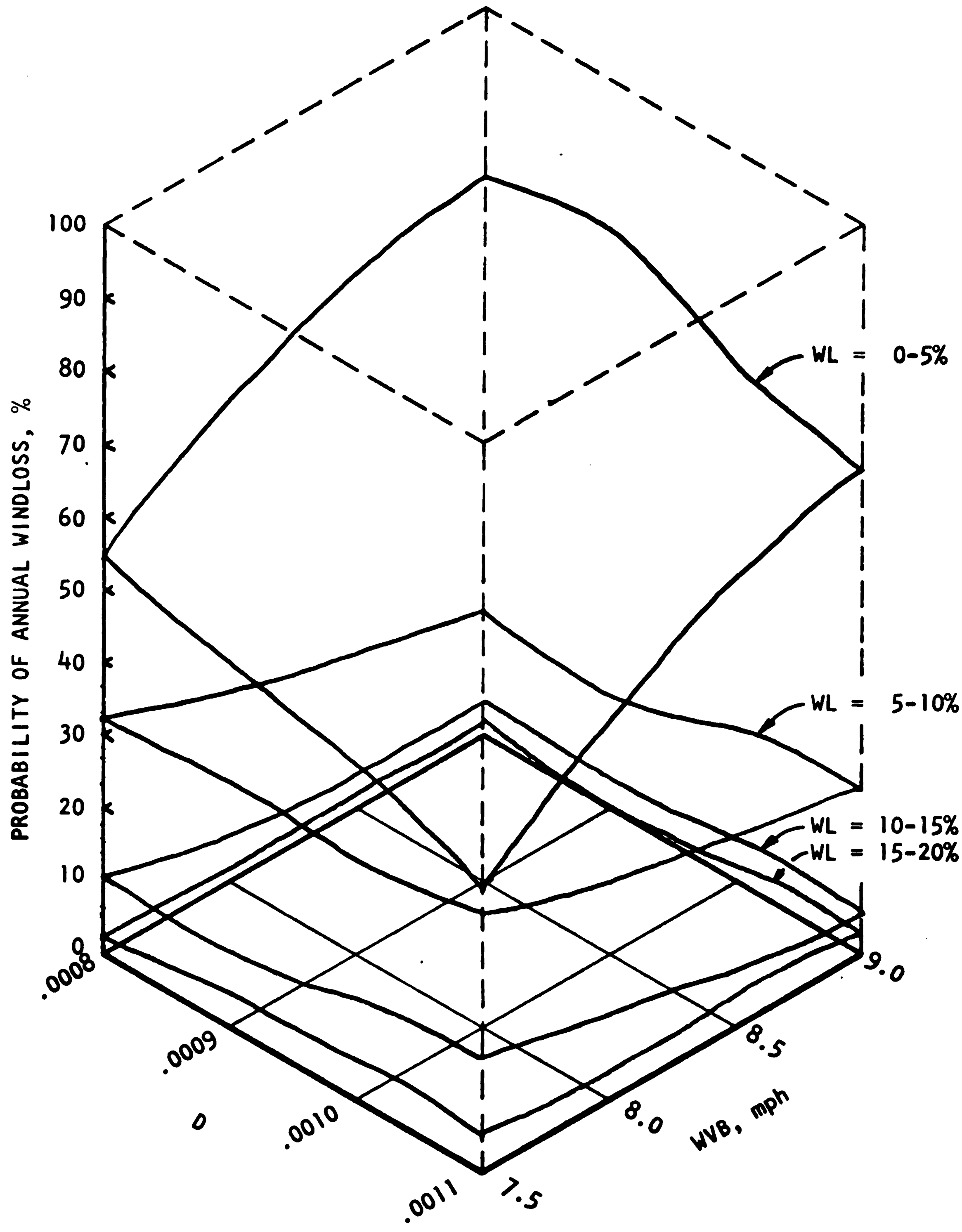

Figure 4.4 Response Surface for Golden Delicious Windloss.

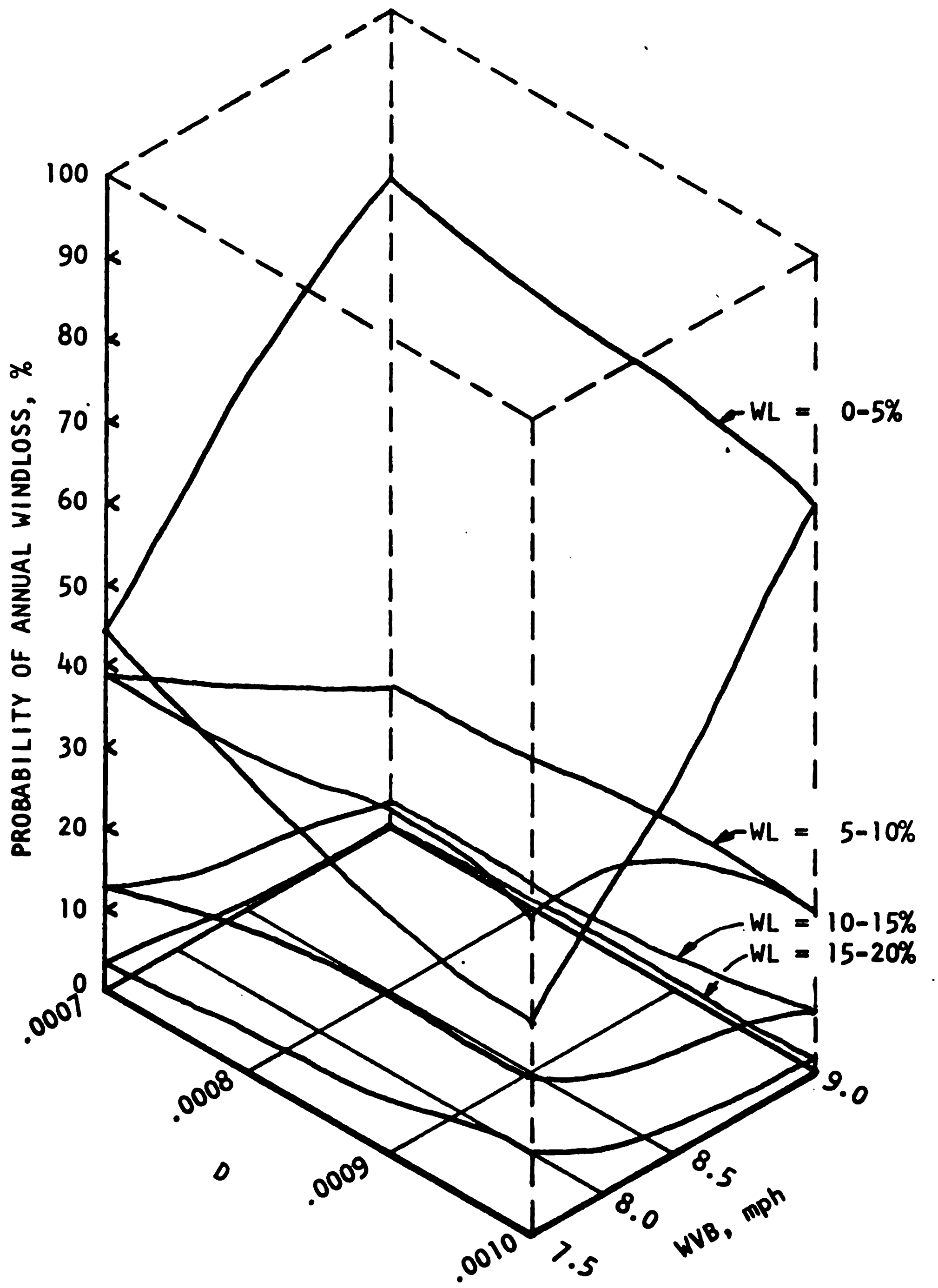

Figure 4.5 Response Surface for Northern Spy Windloss.

Table 4.4. Daily Windloss Model Parameters.

Variety	μ	σ_{μ}	D	WVB	n
	%	%		mph	
McIntosh	12.2	0.28	0.0013	7.0	2
Jonathan	5.9	0.13	0.0007	8.0	2
Golden Delicious	6.0	0.16	0.0010	8.0	2
Northern Spy	6.4	0.16	0.0008	7.5	2

The annual windloss response surfaces were plotted for each variety, to help visualize the effect of changes in D and WVB, and are shown in Figures 4.2 through 4.5.

4.4 Model Verification

The wind velocity distribution formed by the auto-regression model was determined by generating 2400 correlated velocity values, then sorting them into pdf and CDF formats. The generated and observed pdf's differed slightly but the generated and observed CDF's corresponded, Figure 4.1.

Many assumptions have been made in developing the windloss model and in estimating parameters for it. The only verification offered is that the simulated annual windloss pdf and expected value agree closely with those estimated from grower and horticultural agent opinion.

The actual relationships which determine annual windloss are undoubtedly more complex. However, Hillier and Lieberman (11) state that in constructing a model, "all that is required is that there be a high correlation between the prediction by the model and what would actually happen in the real world." It is thought that this windloss simulator meets their requirement, considering the quality of data presently available.

5. HARVEST RATE--ACREAGE RELATIONSHIP

The number of days available for harvesting is determined by fruit maturity requirements and environmental factors such as rain (which may reduce the days available for work) and freezing temperatures or snow (which damage the fruit or terminate harvesting).

The harvest rate--acreage relationship for a mechanical harvest system depends upon: (1) length of the harvest season; (2) varieties and respective acreage; (3) harvest rate; (4) accumulated working hours during the harvest season; and (5) harvest policy of the grower or operator. The first four of these can be determined from available data or specified as a parameter of the harvest system. The question of harvest policy was considered as a choice between two alternatives: (1) begin harvesting each variety when minimum maturity is reached and continue at a constant rate until harvest is completed, not exceeding the date of maximum acceptable maturity; or (2) delay the start of harvest for each variety by up to 7 days, hoping for increased yield due to sizing and accepting the risk of less yield due to windloss, then harvesting at a high rate so as to complete harvest by the same date as for (1). The first policy is referred to as Maximum Acreage, and the second as Delayed Harvest.

5.1 Available Data

5.1.1 Length of the Harvest Season

The typical length of the harvest season beginning with McIntosh and ending with Northern Spy was estimated[2] as six weeks with completion about November 1 (to avoid freezing temperatures and fruit loss). The season may start early or late, but will have a 6-week length.

For a given season, the early, most likely, and late starting dates[3] for each variety are given in Table 5.1. These correspond to dates recommended for apples going into controlled atmosphere storage. The typical length of harvest for each variety was assumed to be the same as given in Table 4.2.

5.1.2 Varieties and Respective Acreage

The four varieties, in acreage proportions given in Section 2.8, were assumed as a representative cross-section. The total acreage was determined by an iterative procedure which is discussed later in Section 5.2.

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[2]Personal communication, Frank Klackle, Dist. Ext. Hort. Agent, Grand Rapids, Mich.

[3]Personal communication, Dr. D. H. Dewey, Professor, Hort. Dept., Mich. State Univ., E. Lansing, Mich.

Table 5.1. Harvest Starting Dates, Grand Rapids Area.

Variety	Early	Most Likely	Late
McIntosh	Sept. 10	Sept. 17	Sept. 24
Jonathan	Sept. 20	Sept. 27	Oct. 4
Golden Delicious	Oct. 10	Oct. 17	Oct. 24
Northern Spy	Oct. 10	Oct. 17	Oct. 24

5.1.3 Harvester Capacity

Harvest rate was considered as a Controllable Input and Design Parameter in Section 2.5. Harvester capacity, in total acres per season, was determined by the iterative procedure (Section 5.2) for several specified harvest rates.

5.1.4 Accumulated Working Hours

Five events were considered to control the number of working hours per season: (1) length of the harvest season; (2) defined work week; (3) work time lost due to rain; (4) work time lost due to machine failure; and (5) waiting time between completion of one variety and start of the next.

The length of harvest season has been established at six weeks. The defined work week was assumed to be six days and eight hours per day (8 AM-5 PM, no Sunday work).

The work time between successive machine failures was assumed to be exponentially distributed, a common assumption for well maintained equipment, with a mean occurrence time of 80 hours.[4] Each failure was assumed to cost four hours of work time or the balance of the workday if less than four hours remained at failure.[4] The waiting time between varieties was determined by the required completion date of one variety and the beginning date for the next.

The work time lost due to rain was determined by the procedure discussed below.

5.1.5 Work Time Lost Due to Rain

Hourly precipitation records for the Kent County Airport, Grand Rapids, were analyzed for the period 1951-1970. The following criteria[5] were used for estimating work time lost due to rain: (1) a rain of 0.20 inches per hour or more during the period 5 PM-8 AM would result in four hours of work time lost during the following 8 AM-12 Noon period; (2) a rain of 0.03 inches per hour, or more, during the normal work period would result in that hour and the remaining hours until 12 Noon (for rain in morning) or 5 PM (for rain in the afternoon) being lost. The daily observations of lost time due to rain were

[4] Based on the author's experience.

[5] Personal communication, N. D. Strommen, State Climatologist, Mich. Weather Service, E. Lans., Mich.

determined for the 20-year period. The results were in agreement with grower opinion in that an average of one-half day per six-day week will be lost to rain.

5.2 Maximum Acreage Policy

A program, which used the information described in Section 5.1, was designed to estimate the maximum acreage which could be completed 90 and 95% of the years for specified harvest rates. The actual lost time observations due to rain were used in this analysis and 50 iterations were made for each of the early, most likely, and late starting dates. A stochastic model for lost time was designed later, Section 5.3, when a continued need for such a model was apparent.

Starting date did not significantly affect the maximum acreage, assuming a constant season length. The average results are given in Table 5.2. Coefficient of variation for total acres ranged from 1.1 to 1.7%.

The range in number of days between completion of one variety and beginning of the next is given in Table 5.3. Generally, there were about five idle days per season due to waiting for the next variety to reach proper maturity. Personal discussion with two representatives of large apple processors suggested that any variety could be harvested five days early, if occasionally necessary, to improve the harvest schedule. The acreage remaining to be harvested in the one or two years out of 20 (which

Table 5.2. Harvest Rate--Acreage, Maximum Acreage Policy.

Harvest Rate (trees/hr)	Total Acres					
	Sept. 10		Sept. 17		Sept. 24	
	.90	.95	.90	.95	.90	.95
10	69.6	65.6	68.8	65.6	67.1	64.8
15	104.4	98.4	103.2	98.4	100.6	97.3
20	139.1	131.3	137.6	131.2	134.2	129.6
25	173.9	164.1	172.0	164.0	167.7	162.1
30	208.7	196.9	206.4	196.8	201.2	194.5

Table 5.3. Idle Days Between Varieties, Maximum Acreage Policy.

Varieties (finished/ started)	Idle Days					
	Sept. 10		Sept. 17		Sept. 24	
	.90	.95	.90	.95	.90	.95
McIntosh/ Jonathan	1-4	0-4	0-5	1-5	1-5	1-5
Jonathan/ G. Delicious	0-5	1-5	0-5	1-6	0-5	1-6
G. Delicious/ N. Spy	0	0	0	0	0	0

determined the .95 and .90 probability level of completion) equalled about one full day of operation. Thus, if harvest was started earlier (when necessary) and two days were added to the length of the harvest season the maximum acreage values might increase by 10%. However, the calculated values will be assumed to hold.

5.3 Delayed Harvest Policy

A second program was designed for use in estimating the expected change in harvested volume, annual windloss volume, and associated risk levels faced by a grower considering the Delayed Harvest Policy.

The McIntosh variety was examined first. A 40-acre planting, at 27 trees per acre, and a harvest rate of 15 trees per hour were assumed in order to establish a nominal harvest period of 10 days. Eight identical harvest systems were assumed to begin harvesting on day 1, day 2, ... day 8, each with a harvest rate sufficient to complete the 40 acres by the same date. For purposes of simplicity, machine recovery was assumed at 100%, fruit injury at 0%, and machine breakdowns at zero. The yield model, windloss model, and daily growth rate already discussed were used in this program. In addition, stochastic models for lost time due to the occurrence of a Sunday or rain were used.

The model for lost time due to a Sunday consisted of comparing a uniform (0, 1) random number to the daily probability of occurrence of a Sunday. The successive daily probabilities were 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, and 1/1. The first Sunday occurred when the random number was less than the daily probability. Succeeding Sundays were then specified at 7-day intervals.

The model for lost time due to rain used a discrete pdf for lost time, Table 5.4, developed from the rain data discussed in Section 5.1.5. Using the method discussed in Section 3.2, the correlation between lost time for successive days was concluded to be zero. Thus, although rain is typically assumed to be a persistent phenomena (i.e., amount on successive days is correlated), lost work time is not a persistent phenomena (for the assumed criteria, Section 5.1.5). Lost time due to rain was generated daily using the inverse transform method. Work time available was equal to eight hours minus the lost time.

Table 5.4. Daily Work Time Lost Due to Rain.

Hours Lost	0	1	2	3	4	5	6	7	8
Probability	0.816	0.007	0.008	0.014	0.107	0.006	0.011	0.012	0.018

The delayed harvest simulation was run for 200 years, summary statistics were calculated, and the annual observations for each harvest policy were sorted into pdf format. The results are summarized in Table 5.5.

The simulation results for McIntosh, at the average growth rate, show that: (1) the harvest ratio (ratio of volume harvested with delay to volume harvested without delay) decreases with length of delay; (2) the mean annual windloss increases with length of delay. However, for growth rates 1 and 2 standard deviations greater than the average: (1) the change in harvest ratio is insignificant; (2) the mean annual windloss increases with length of delay. In addition to these conclusions, the standard deviations for both harvest ratio and windloss suggest that a delayed harvest policy is very risky for McIntosh.

The Jonathan variety has about one-half the tendency for windloss as does the McIntosh and has a longer harvest period. A second simulation was run using data for Jonathan and performing an identical analysis. The results are summarized in Table 5.6.

In general, the conclusions for McIntosh also apply to Jonathan. The decrease in harvest ratio and increase in windloss for the average growth rate are not as great as for McIntosh. The results for growth rates 1 and 2 standard deviations greater than the average both result in a slight increase in harvest ratio. The average

Table 5.5. Delayed Harvest Results, McIntosh.

	Harvest Policy		Harvest Ratio		Annual Windloss	
	Delay	Rate	μ	σ	μ	σ_μ
	Days	Trees/hr			%	%
Average Growth Rate	0	15.00	1.000	--	11.3	0.50
	1	16.88	0.992	0.0096	12.3	0.55
	2	19.29	0.988	0.0187	12.8	0.57
	3	22.50	0.983	0.0280	13.5	0.61
	4	27.00	0.977	0.0356	14.2	0.63
	5	33.75	0.971	0.0426	15.0	0.66
	6	45.00	0.965	0.0516	15.8	0.69
	7	67.50	0.966	0.0517	15.8	0.69
Average Growth Rate + 1 Standard Deviation	0	15.00	1.000	--	11.1	0.49
	1	16.88	0.999	0.0088	12.1	0.54
	2	19.29	0.998	0.0169	12.6	0.56
	3	22.50	0.997	0.0256	13.2	0.59
	4	27.00	0.996	0.0334	13.9	0.62
	5	33.75	0.996	0.0410	14.5	0.64
	6	45.00	0.995	0.0506	15.3	0.67
	7	67.50	0.996	0.0516	15.2	0.67
Average Growth Rate + 2 Standard Deviations	0	15.00	1.000	--	11.0	0.48
	1	16.88	1.005	0.0087	11.9	0.52
	2	19.29	1.008	0.0170	12.3	0.55
	3	22.50	1.012	0.0253	12.9	0.58
	4	27.00	1.015	0.0332	13.5	0.60
	5	33.75	1.019	0.0411	14.1	0.62
	6	45.00	1.024	0.0516	14.8	0.65
	7	67.50	1.025	0.0522	14.7	0.65

Table 5.6. Delayed Harvest Results, Jonathan.

	Harvest Policy		Harvest Ratio		Annual Windloss	
	Delay	Rate	μ	σ	μ	σ_μ
	Days	Trees/hr			%	%
Average Growth Rate	0	15.00	1.000	--	5.5	0.28
	1	16.36	0.999	0.0038	5.8	0.29
	2	18.00	0.997	0.0076	6.1	0.31
	3	20.00	0.996	0.0103	6.3	0.32
	4	22.50	0.995	0.0134	6.6	0.34
	5	25.71	0.994	0.0147	6.9	0.34
	6	30.00	0.992	0.0174	7.2	0.36
	7	36.00	0.993	0.0182	7.1	0.36
Average Growth Rate + 1 Standard Deviation	0	15.00	1.000	--	5.4	0.27
	1	16.36	1.003	0.0037	5.7	0.29
	2	18.00	1.004	0.0074	6.0	0.30
	3	20.00	1.006	0.0099	6.2	0.31
	4	22.50	1.007	0.0128	6.4	0.33
	5	25.71	1.010	0.0141	6.7	0.33
	6	30.00	1.012	0.0168	7.0	0.34
	7	36.00	1.011	0.0174	6.9	0.35
Average Growth Rate + 2 Standard Deviations	0	15.00	1.000	--	5.3	0.27
	1	16.36	1.007	0.0043	5.6	0.28
	2	18.00	1.011	0.0091	5.8	0.29
	3	20.00	1.015	0.0114	6.0	0.31
	4	22.50	1.020	0.0144	6.3	0.32
	5	25.71	1.025	0.0160	6.5	0.32
	6	30.00	1.031	0.0187	6.8	0.33
	7	36.00	1.029	0.0176	6.7	0.34

results and standard deviations suggest that a delayed harvest policy for Jonathan is less risky than for McIntosh but, the expected increase in harvest ratio is not of sufficient magnitude to be economically attractive to commercial growers.

From a positive viewpoint, these results also suggest that if a delay (due to manpower, scheduling, machinery, etc. problems) should occur, and the harvester is capable of a higher harvest rate, the harvested volume will not decrease greatly.

5.4 Harvest Policy Selection

After considering the results of the Maximum Acreage and Delayed Harvest Policies, the former was selected for use in the final harvest simulation model.

Several intangible factors also supported the selection of this policy: (1) a harvest policy should not deliberately expose the grower to an increased risk of substantial financial loss; (2) high growth rates are required for a delayed harvest policy to have a low risk of financial loss, but only an indication of growth rate is available at the actual start of harvest; (3) many of the harvest rates required in the Delayed Harvest Policy are well in excess of those attainable in the near future on standard type trees; (4) the material handling problem (scheduling of bulk bin delivery and pickup) becomes critical, by present standards, when the harvest period is compressed; and (5) the effect of machine failure (not included in the delayed harvest simulation) becomes critical as the harvest period is compressed.

6. HARVEST SIMULATION MODEL

The program HARVSIM uses all inputs and models discussed in previous chapters to simulate both hand and mechanical harvesting of apples for processed utilization. HARVSIM is written in FORTRAN IV and requires about 22,000 octal units of central memory to compile and run on the CDC 6500 Computer.

A simplified flow-chart of HARVSIM is given in Figure 6.1 to show the simulation sequence and subroutines used. The entire program is described in "HARVSIM--Evaluation of mechanical harvest methods for processing apples via simulation" which was submitted for publication in the MSU, Agricultural Engineering Department Preprint Series.

6.1 Initialization

The number of simulations completed before the output statistics are calculated and printed is controlled by NG, i.e., the number of growers assumed in the sample which the statistics represent. Any number can be set without changing the input required or output format used.

The basic dimensions of the simulation are controlled by: (1) NY, the period of consecutive years

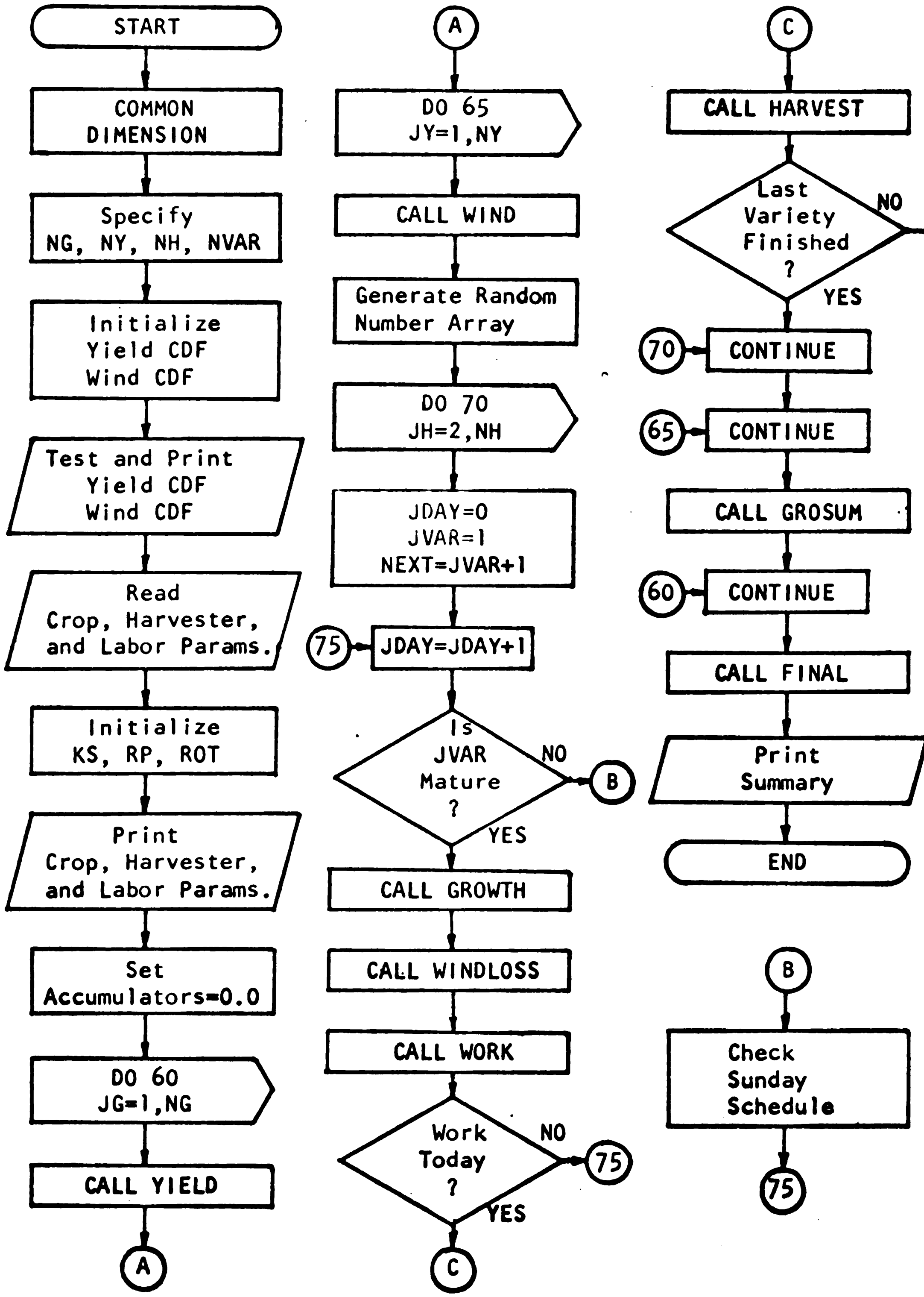

Figure 6.1 Simplified Flow Chart of HARVSIM.

analyzed for each grower; (2) NH, the number of harvest methods analyzed in the simulation; and (3) NVAR, the number of varieties considered in each simulation. Changes in NY or NVAR will require corresponding changes in input data and output format used. A change in NH requires a corresponding change in input data, but no change in output format.

The CDF for annual yield of each variety and for daily average wind velocity are each initialized using yield or velocity values and the corresponding cummulative probability values. Function TABLI (16), a FORDYN program, computes the uncorrelated yield and velocity values based on the initialized CDF's. Initialization is checked by printing 21 points of each CDF (from 0.0 to 1.0) and the corresponding yield or velocity values, using function TABLI.

The crop parameters, harvest parameters, and labor costs are read in from three groups of data cards. The most likely number of days between start of harvest for the successive varieties are established with the variables KS(JVAR). The typical decay and recovery of windfall apples are established for each variety using ROT(JVAR) and RP(JH). The initialized values for the three categories of parameters are then printed for a check on initialization and future reference.

6.2 Subroutine YIELD

A new set of correlated yields for each variety are generated for NY years, for each grower, and stored in a yield array.

6.3 Subroutine WIND

A new set of correlated daily average wind velocities are generated for each year and stored in a wind velocity array.

6.4 Random Number Array

Separate series of consecutive uncorrelated random numbers (0,1) are generated and stored for use in determining occurrence of the first Sunday, lost time due to rain, and machine breakdowns. By storing these numbers at this time, each harvest method can work through the harvest season on the same schedule, have the same daily rain occurrences, and the same failure times.

6.5 Subroutine GROWTH

Growth of on-tree yield is assumed to occur at an average rate between each successive day after maturity is reached. If the next variety is mature, but is not yet being harvested, the appropriate growth rate is also applied to it.

6.6 Subroutine WINDLOSS

Windloss of on-tree yield is assumed to occur on each day after maturity is reached. If the next variety is mature, but is not yet being harvested, windloss is also calculated for it. Windloss is a function of wind velocity each day and the windloss-velocity relation for the respective variety. This subroutine first calculates the windloss (percentage loss of on-tree yield each day), then calculates the actual on-tree yield and on-ground yield for day i.

6.7 Subroutine WORK

The harvest time available each day depends on: (1) if the day is a Sunday or workday; (2) if work time is lost due to rain; and (3) if a machine breakdown occurs. Using the previously generated random numbers, these events are determined daily by this subroutine and a value for HT ($0.0 \leq HT \leq 8.0$) is calculated.

6.8 Subroutine HARVEST

If HT is greater than zero, harvest proceeds. The volumes harvested, remaining trees, and hours of operation are accumulated, and control returns to the main program where JDAY advances by 1 and the process is repeated. When one variety is finished, the next is started on the same day if it is mature. When all varieties are completed, HARVEST instructs the main program to advance to the next harvest method and the season is repeated.

6.9 Subroutine GROSUM

When all specified harvest methods and years have been completed for one grower, this subroutine calculates the sums and sums-of-squares of the output variables for later use in calculating expected values and standard deviations.

6.10 Subroutine FINAL

When the simulations have been completed for all growers, the expected value and standard deviation of each output variable are calculated.

6.11 Output

The results calculated in FINAL are given in tabular form with appropriate labelling and footnoted explanations.

Summaries, rather than yearly values for the output variables, are given for ease of analysis. The results are determined by a combination of several random processes. The actual observations can be used to estimate the pdf for each variable, which in turn can be used to estimate the probability of occurrence of certain values for each variable.

7. HARVEST SIMULATION

Input information required for HARVSIM was used to simulate results for growers with 70 acres of mature, standard type, apple trees (the four varieties in proportions given in Section 2.8) and two sizes of mechanical harvest systems. The expected value and standard deviation were calculated for each output variable listed in Section 2.4. Histograms for each output variable were inspected for reasonable similarity with the Normal Distribution, and the probability of negative margin and planning margin were estimated. Finally, to determine the effect of input parameter changes on output variable values, a sensitivity analysis was conducted.

7.1 Simulation Assumptions

The two mechanical harvest systems were assumed to be self-propelled, and commercially available in 1968 at $15,700 for a 10 tree per hour system and $19,600 for a 15 tree per hour system. The equipment costs are thought to be representative estimates for each harvest system in 1968.

The mechanical harvesting of apples is not an established practice in any part of Michigan. During the first few years of transition from hand harvest methods to mechanical harvest methods, machine obsolescence will occur in a short period of time. An even number of years should be used for the planning period because annual yields are biennial, as discussed in Chapter 3. In addition, the simulation results will be more representative if the most recent input data available is used. Because of these facts, a four-year machine life and planning period, 1968-1971, was assumed.

The yield for each variety, generated by subroutine YIELD, was assumed to be independent of the yield for the other varieties. This assumption was made because the four varieties being used represent a cross-section of the varieties a grower may have, and enough accurate data is not available from which correlations between varieties can be statistically confirmed. An assumption that yield for each variety will vary in the same pattern would result in higher standard deviations, but the same expected values, for margin and planning margin.

Estimates for the portion of yield: (1) 2½-inch diameter and larger; and (2) with natural defects, were obtained for fruit of each variety.[6]

Estimates for the portion of yield: (1) removed from the tree; and (2) with excessive harvest injury,

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[6]Personal communication, Frank Klackle, Dist. Ext. Hort. Agent., Grand Rapids, Mich.

for each variety were also obtained.[7] The estimates for each mechanical harvest system are optimistic, i.e., the best results anticipated.

The volume of apples recovered as windfalls, and the ratio of windfalls for the mechanical harvest methods compared to the hand harvest method were computed. However, the cost of recovering windfalls and the value of windfalls were not used in determining margin and planning margin because most growers do not have a dependable market for this class of fruit.

The piece rate for hand picking given by Kelsey, Harsh, and Belter (15) was assumed for 1970. Costs for other years were estimated by assuming a 5% increase between successive years.

The hourly cost for labor was assumed at a higher level than normally paid for agricultural labor. Crews operating mechanical harvesters are often paid on an incentive plan to encourage high productivity and discourage careless operation or practices which decrease fruit quality. Also, if wages comparable to those in manufacturing could be paid for agricultural labor, worker earnings and the supply of labor for agricultural work would both increase. For these reasons the hourly cost

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[7]Personal communication, J. H. Levin, Invest. Ldr., Fruit and Veg. Harv. Invest., USDA-ARS-AERD, E. Lans., Mich.

of labor was assumed comparable to the average hourly wage in manufacturing for the State of Michigan (20).

All assumed crop, price, and labor cost parameters are given in Table 7.1, and harvest system parameters are given in Table 7.2, under the appropriate name as described in Sections 2.2 and 2.3.

Accurate outputs from HARVSIM depend on: (1) accurate input information; (2) valid model formulation and accurate parameter estimation; and (3) the number of growers (i.e., number of independent observations) included in the simulation. Of the output variables given in Section 2.4, the most important is planning period margin. The number of growers to include in the simulation was determined by using HARVSIM results for 80 growers to estimate the standard deviation of: (1) the mean of expected planning margin (EPMAR); and (2) the standard deviation of planning margin (SDPMAR). The change in accuracy of estimating EPMAR and SDPMAR with a change in the number of growers was then considered. The above standard deviation estimates were determined by the relations:

$$S_{\bar{Y}} = \frac{S_Y}{\sqrt{n}}$$

Where:

Table 7.1. Assumed Crop, Price, and Labor Cost Parameters.

Year	Parameter	McIntosh	Jonathan	Golden Delicious	Northern Spy
All	PG	.90	.85	.90	.90
All	DNAT	.02	.03	.03	.04
All	ACRES	17.50	31.50	9.10	11.90
All	TREED	27.	34.	34.	27.
All	ROT	.10	.10	.10	.10
1968	PRICE (PR)	3.25	4.25	4.25	4.25
1969	PRICE (PR)	2.25	3.00	3.00	3.25
1970	PRICE (PR)	2.00	2.25	2.25	2.50
1971	PRICE (PR)	2.00	2.25	2.25	2.50
1968	PRICE (JU)	1.75	1.75	1.75	1.75
1969	PRICE (JU)	1.25	1.25	1.25	1.25
1970	PRICE (JU)	1.00	1.00	1.00	1.00
1971	PRICE (JU)	1.00	1.00	1.00	1.00

Parameter	Year			
	1968	1969	1970	1971
OCOST	3.50	3.75	4.00	4.20
PCOST	.35	.37	.39	.41

Table 7.2. Assumed Harvest System Parameters.

Harvest Method	Parameter						
	ECOST	ELIFE	TII	RFO	OPER	HRATE	RP
Hand					10	10	.50
Mechanical (3)	15700	4	.10	5.00	4	10	.80
Mechanical (4)	19600	4	.10	5.00	4	15	.80

Harvest Method	Parameter	Variety			
		McIntosh	Jonathan	Golden Delicious	Northern Spy
Hand	RH	.99	.99	.99	.99
	HI	.03	.02	.02	.02
Mechanical (3)	RH	.98	.95	.97	.98
	HI	.07	.04	.04	.04
Mechanical (4)	RH	.98	.95	.97	.98
	HI	.06	.03	.03	.03

$S_{\bar{y}}$ = Standard deviation of the mean

S_y = Standard deviation of the observations

n = Number of observations

and

$$S_s = \frac{S_y}{\sqrt{2n}}$$

Where:

S_s = Standard deviation of S_y

The relation of $S_{\bar{y}}$ is valid for samples from any population with finite variance and the relation for S_s holds for samples of $n \geq 15$ from a population considered to be normally distributed (26). Planning margin can be considered normally distributed as discussed in Section 7.2.

For 80 growers the standard deviation of the mean of EPMAR was about 195, or 3-7% of EPMAR depending on the harvest system, and the standard deviation of SDPMAR was about 140, or 8% of SDPMAR. Because both standard deviation values vary inversely with the square root of the number of observations, corresponding standard deviation values for 40 growers should be about 1.4 times greater than for 80 growers. Similarly, values for 80 growers should be about 1.4 times greater than for 160 growers. The accuracy obtained by including 80 growers in the simulation was considered adequate.

7.2 Simulation Results

The expected values and standard deviations for the output variables are given in Tables 7.3 and 7.4. Harvester number 3 is the $15,700 system with a harvest rate of 10 trees per hour and harvester number 4 is the $19,600 system with a harvest rate of 15 trees per hour.

The results in Table 7.3 show that:

1. Expected margin increased steadily since 1968 (the only year in which expected margin was negative for either harvest system).
2. Expected planning margin was positive for both harvest systems but system 4 was $4,300 higher than system 3. The increased margin was due to the assumed wage rates and annual savings in man-hours for harvesting with system 4 compared to system 3.
3. If successive yields were independent, the standard deviation of planning margin would be equal to the square root of the sum of the squared standard deviations of margin, Table 7.3. However, the negative correlation used in the yield model caused the standard deviation of planning margin to be 36% less than would result if successive yields were independent (planning margin is the sum of four correlated margins). Thus, when expected planning margin is positive, the probability of negative planning margin is less than would result if successive yields were independent.

Table 7.3. Simulated Margin and Harvest Cost.

Harvester Number	Statistics[1]	Planning Period Year				EPMAR
		1968	1969	1970	1971	SDPMAR
		YMAR Statistics (dollars)				
3	EYMAR	-695.13	587.68	1254.73	1714.49	2861.77
	SDYMAR	1063.54	1262.17	1593.34	1358.06	1709.86
4	EYMAR	559.35	1647.47	2118.37	2805.55	7130.74
	SDYMAR	1204.45	1289.77	1630.77	1415.78	1784.52
		HC Statistics (dollars/bu)				
3	EHC	.312	.309	.322	.323	
	SDHC	.050	.046	.054	.042	
4	EHC	.297	.292	.303	.300	
	SDHC	.047	.042	.051	.038	

[1] Statistic corresponds to output name as described in Section 2.4.

Table 7.4. Simulated Productivity and Volume Ratios.

Harvester Number	Statistics[1]	Apple Variety			
		McIntosh	Jonathan	Golden Delicious	Northern Spy
		Worker Productivity (bu/man-hr)			
3	EPROD	37.3	30.8	30.7	32.6
	SDPROD	10.8	6.8	8.9	12.4
4	EPROD	57.1	46.8	46.6	49.2
	SDPROD	16.4	10.2	13.3	18.5
		Harvested Volume Ratios (mech/hand)			
3	EPR	.9462	.9382	.9572	.9679
	SDPR	.0073	.0049	.0130	.0164
	EJR	.9462	.9382	.9572	.9679
	SDJR	.0073	.0049	.0130	.0164
	EDR	1.6844	1.6934	2.1641	2.1078
	SDDR	.1818	.1588	2.0008	.8159
4	EPR	.9766	.9593	.9818	.9861
	SDPR	.0228	.0148	.0424	.0333
	EJR	.9766	.9593	.9818	.9861
	SDJR	.0228	.0148	.0424	.0333
	EDR	1.1118	1.0875	.6428	.7651
	SDDR	.2855	.2436	.3998	.4786

[1]Statistic corresponds to output name as described in Section 2.4.

4. Overall cost per bushel for mechanical harvesting remained relatively constant over the four-year period.

The results in Table 7.4 show that:

1. Worker productivity for system 3 was about three times higher, and for system 4 was about five times higher, than for hand picking assuming an expected productivity of 10 for hand picking (23).
2. The standard deviation of productivity was 22-38% of the expected value, depending on the variety and harvest system.
3. The harvested volume ratios for system 3 indicate that 3-6% less volume per grower, depending on variety, would be available for processing or juicing by processors. Similar ratios for system 4 indicate that 2-4% less volume would be available.
4. The harvested volume ratio for windfalls for system 3 indicates that 68-116% more volume would be available for sale (at the assumed recoveries for hand and mechanical harvest) with mechanical harvesting. The increased volume is a combined result due to equipment breakdown and higher recovery of windfalls with a mechanized system. No shortage of labor was assumed for hand harvesting but recovery of windfalls is usually low because windfalls are picked up by hand if a ready market exists after hand picking is completed.

5. The harvested volume ratio for windfalls for system 4 indicates 11% more to 35% less volume available for sale with mechanical harvesting. This occurs because system 4 has a higher harvest rate than needed by the assumed 70-acre grower, thus each variety is harvested in a shorter time period than required for hand harvest.

The probability that margin (YMAR) or planning margin (PMAR), for an individual grower, may be less than or greater than a particular value can be estimated using the results in Table 7.3, if the respective YMAR or PMAR pdf is known. Since each grower in the sample is independent of all other growers, and the correlation between yield for all varieties each year is zero, the yearly YMAR observations and the summary PMAR observations are independently distributed about their expected values. The pdf of each output variable was estimated by sorting the individual observations into a frequency histogram which was centered on the expected value and divided into six parts of one standard deviation each. By inspection of the histograms it was concluded that YMAR, PMAR, and productivity (PROD) could be assumed to follow the Normal Distribution. However, the histograms for harvest cost (HC) and windfall ratio (DR) were skewed to the right of the mean and those for processing ratio (PR) and juice ratio (JR) were skewed to the left of the mean. Thus, these latter random variables are probably not normally distributed.

The probability of negative YMAR and PMAR was estimated using the assumption that YMAR and PMAR are normally distributed. The results for harvest system 3, Table 7.5, show that the risk of negative YMAR steadily declined from 0.74, the first year of the planning period, to 0.19, the last year of the planning period, and that the risk of negative PMAR is only 0.05. The trend is similar for harvest system 4 but the corresponding risks are less than one-half those for harvest system 3.

Table 7.5. Risk of Negative Margin.

Harvester Number	YMAR				PMAR
	1968	1969	1970	1971	1968-71
3	0.74	0.32	0.21	0.19	0.05
4	0.38	0.10	0.10	0.02	0.00+

7.3 Sensitivity Analysis

A sensitivity analysis can provide: (1) greater insight to the inner workings of the simulation model; (2) an identification of the critical and less critical parameters; (3) an indication whether some of the constraints should be loosened or tightened; and (4) a more quantitative idea about the expected overall performance of the system being modeled (1).

Twelve parameters were selected for inclusion in a sensitivity analysis on expected margin and expected planning margin performed for both mechanical harvest systems. One parameter at a time was varied and the corresponding outputs were calculated by HARVSIM. To reduce computer time, but still obtain acceptably accurate expected values, only 40 growers were included. Each complete simulation was made using the same series of random numbers, so the difference in output was due only to the harvest system and the particular combination of parameter values. The initial parameter values were the same as used in the previously discussed simulation for 80 growers, Tables 7.1 and 7.2.

The sensitivity results are given in Figures 7.1-7.12 for harvest system 3, and Figures 7.13-7.24 for harvest system 4. The initial parameter values are indicated by the symbol ▲ along the horizontal axis of each figure. Variation in parameter value is given in absolute value, factor value, or delta value (Δ) depending on the parameter. Factor values are simply 0.75, 1.00, or 1.25 times the initial absolute value of the parameter. Delta values are a constant difference from the initial absolute values and were used when the initial absolute value was different for each variety, quality class, or year. The sensitivity to parameter variation is indicated by dashed lines for expected margin (EYMAR) and by a solid line for expected planning margin (EPMAR).

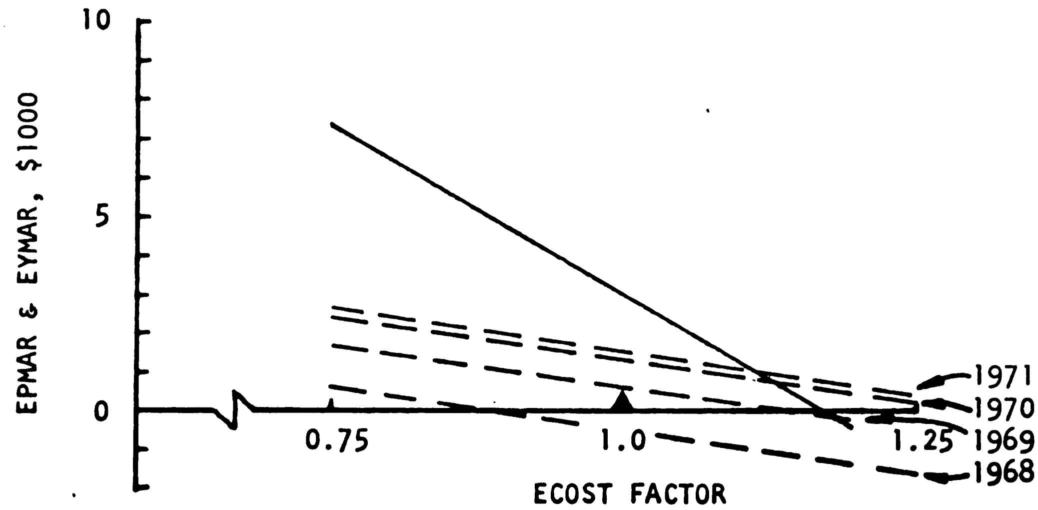

Figure 7.1 Sensitivity to Equipment Cost.

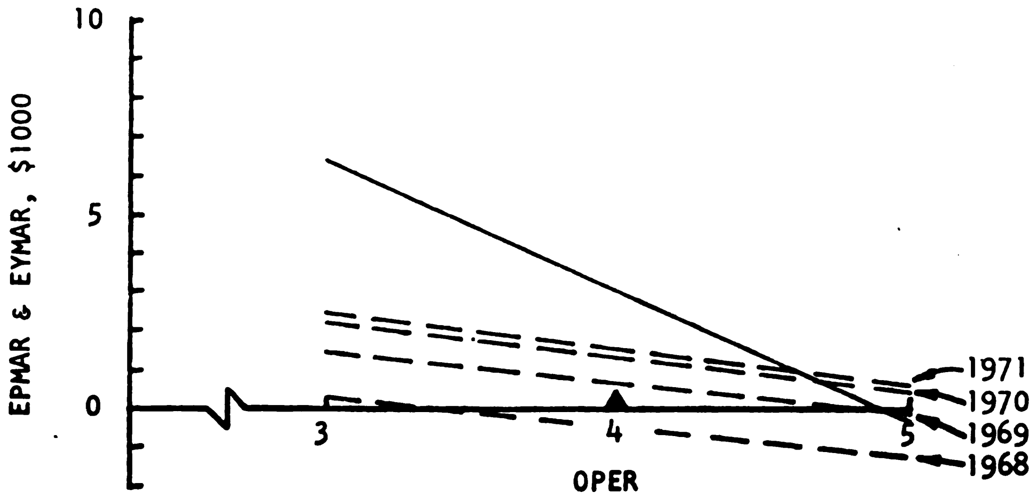

Figure 7.2 Sensitivity to Crew Size.

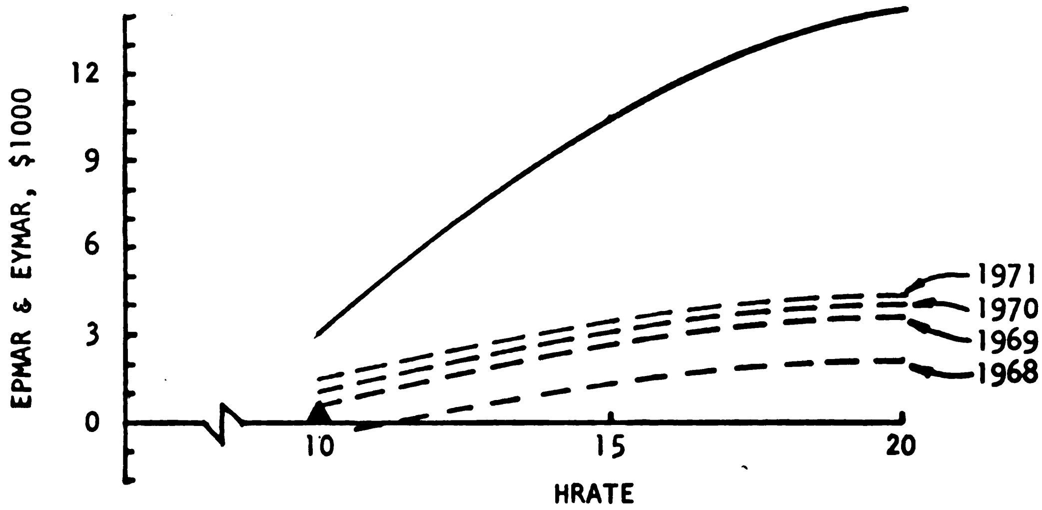

Figure 7.3 Sensitivity to Harvest Rate.

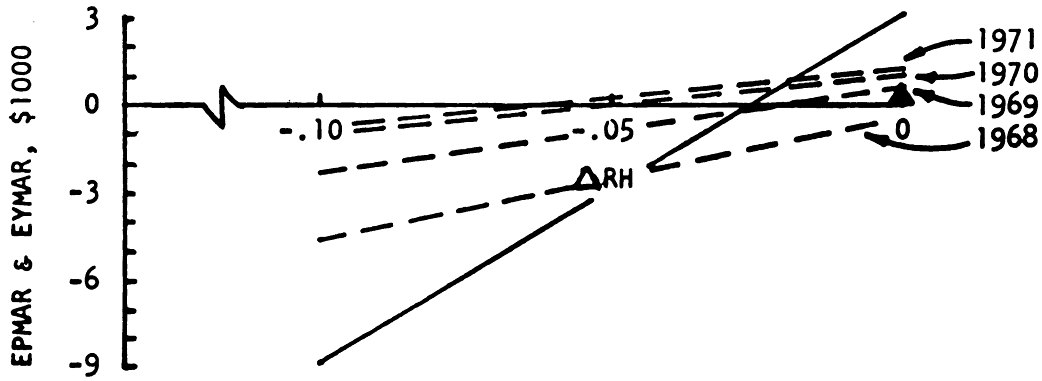

Figure 7.4 Sensitivity to Machine Recovery.

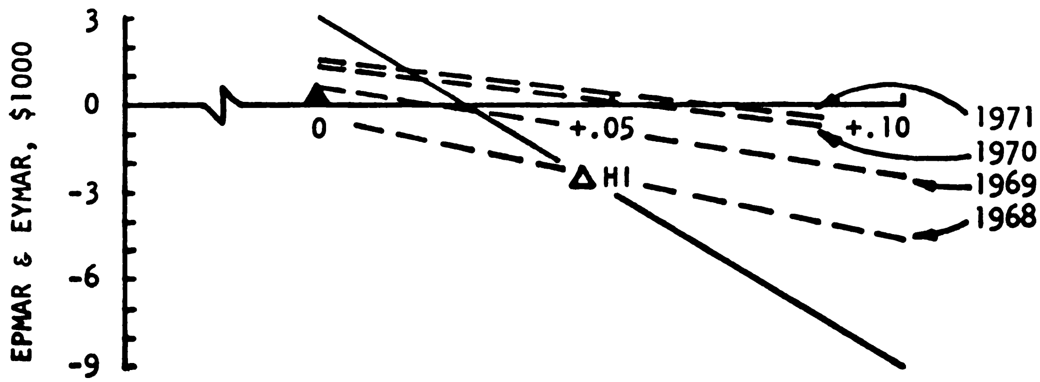

Figure 7.5 Sensitivity to Fruit Injury.

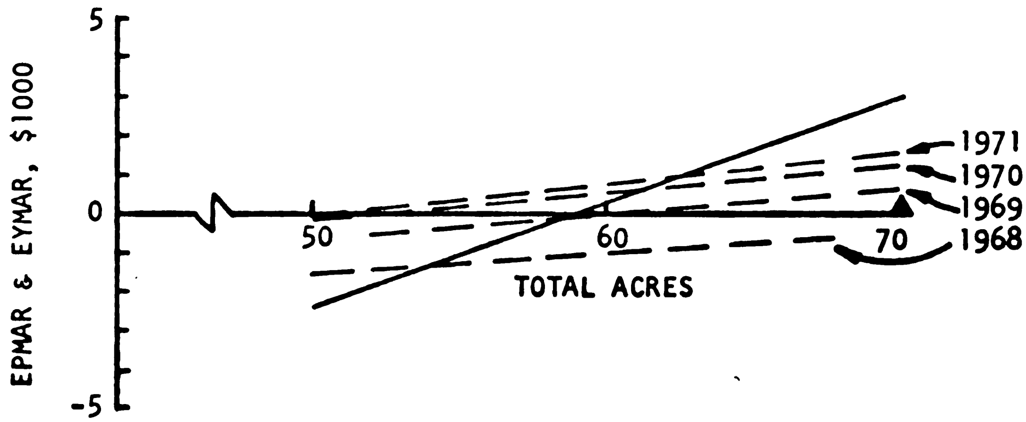

Figure 7.6 Sensitivity to Total Acreage.

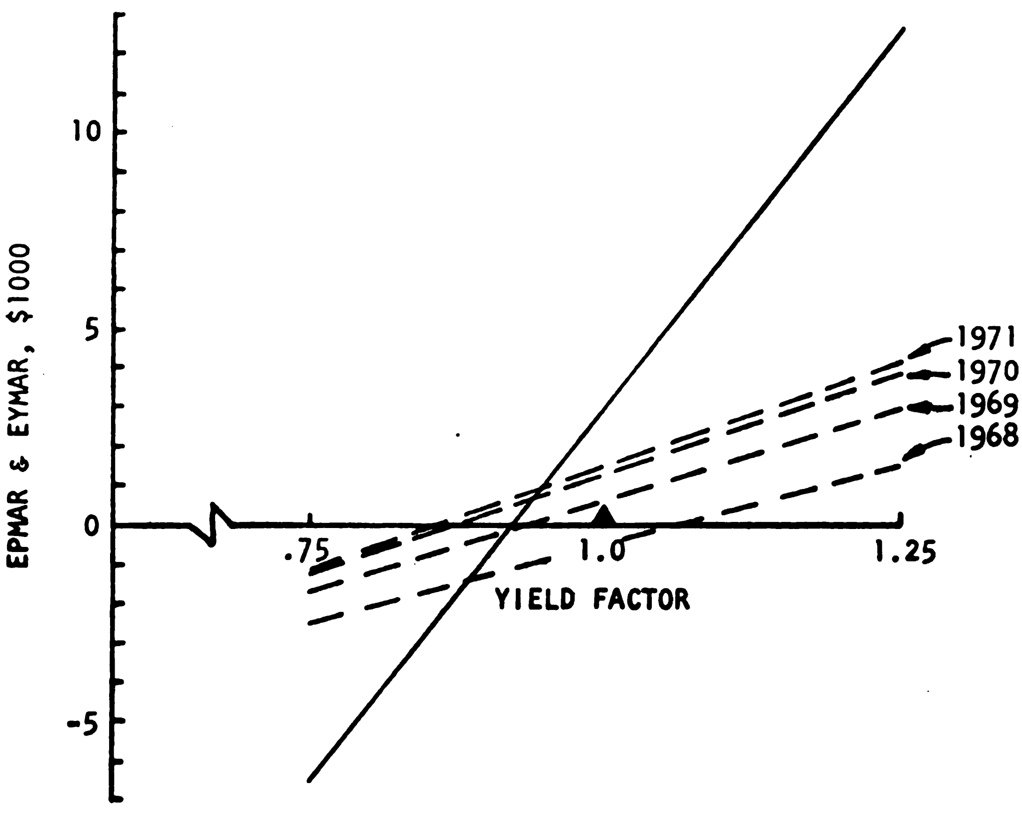

Figure 7.7 Sensitivity to Yield.

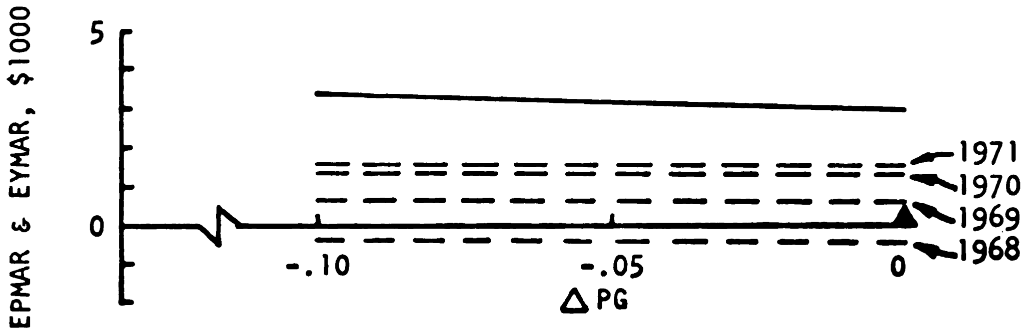

Figure 7.8 Sensitivity to Fruit Size.

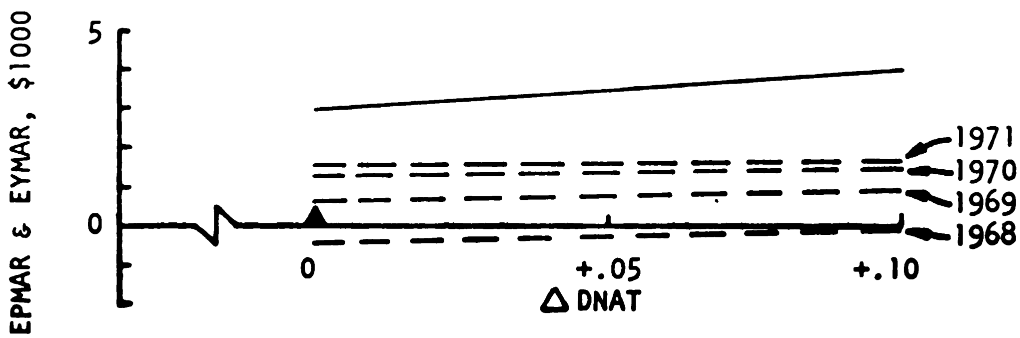

Figure 7.9 Sensitivity to Natural Defects.

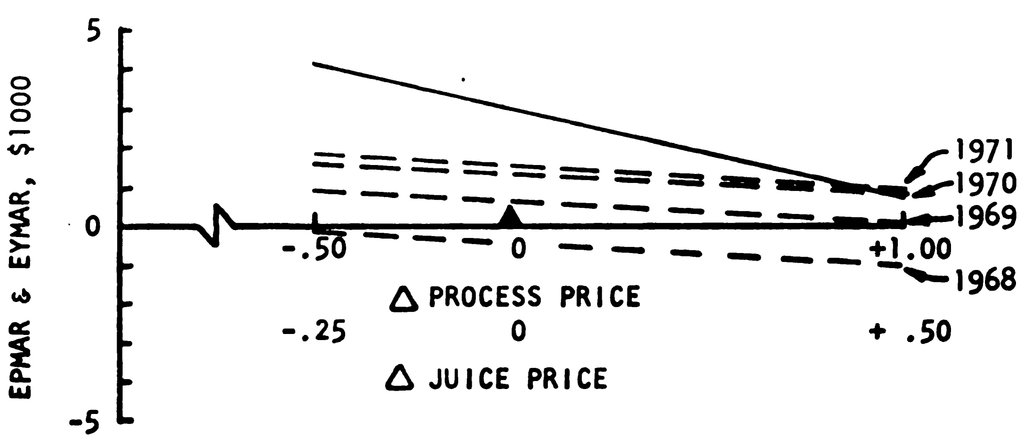

Figure 7.10 Sensitivity to Fruit Price.

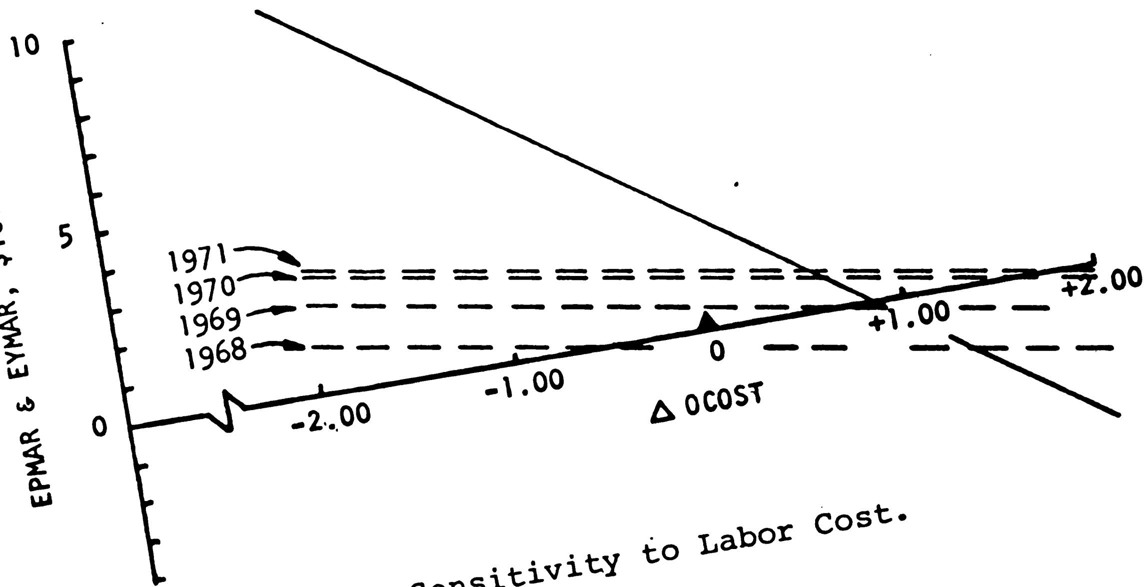

Figure 7.11 Sensitivity to Labor Cost.

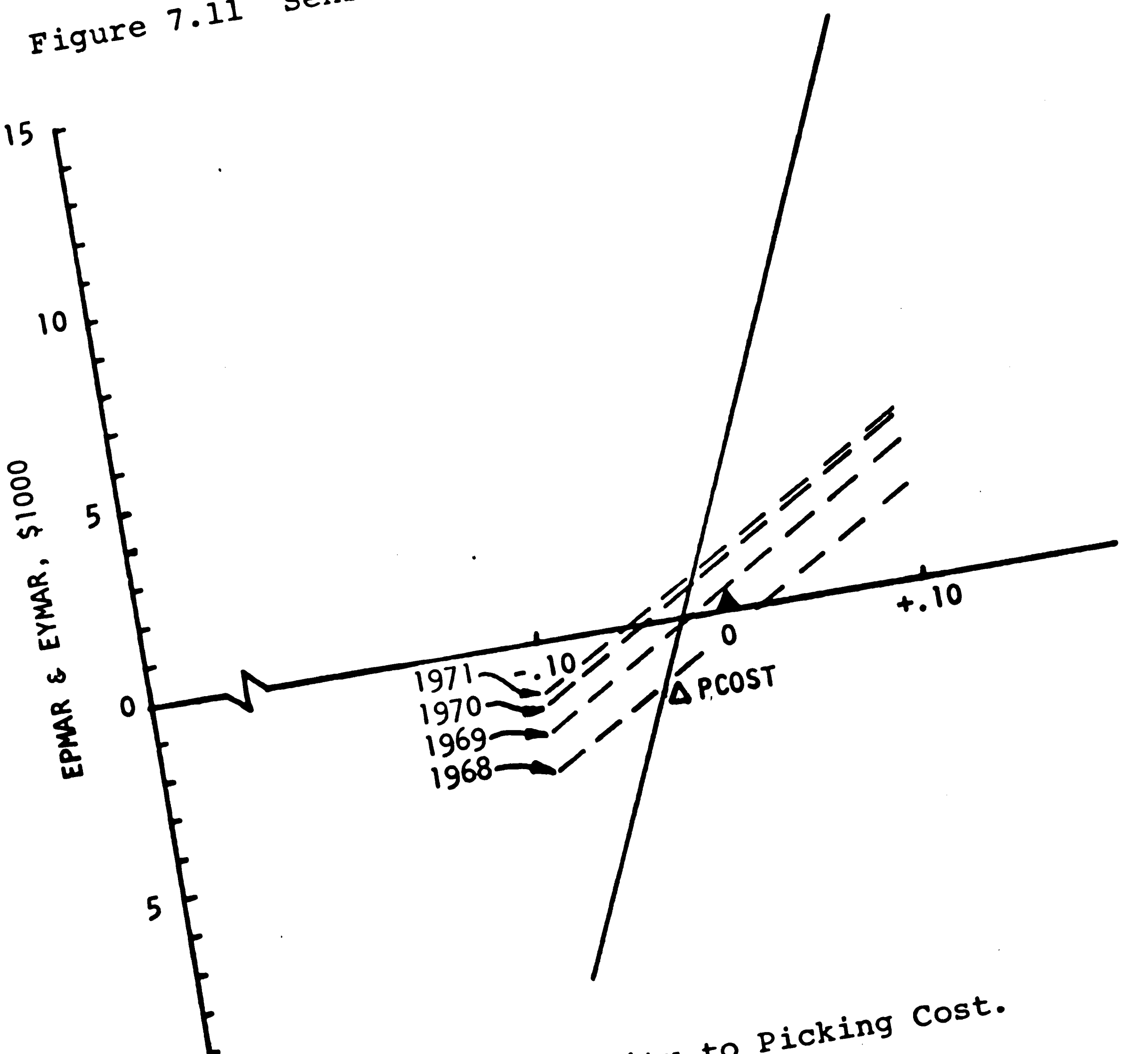

Figure 7.12 Sensitivity to Picking Cost.

The sensitivity analysis for harvest system 3 shows that:

1. The relation between EYMAR or EPMAR and all parameters is linear, with the exception of harvest rate, Figure 7.3, which has a positive curvilinear relation.
2. EYMAR and EPMAR are sensitive to variation in all parameters, but are least sensitive to variation in fruit size, Figure 7.8, and natural defects, Figure 7.9. Input information on fruit size and natural defects need not be described stochastically or extremely accurate for simulation purposes unless actual variation is greater than presently assumed.
3. The magnitude of EYMAR increased each successive year, but its slope remained nearly constant.
4. EYMAR and EPMAR increase as fruit price decreases, Figure 7.10. The large change in fruit price between 1968 and 1970 accounts for the large change in EYMAR between 1968 and 1970. Low fruit price, typical of 1970 and 1971, favors use of mechanical harvest systems.
5. A relatively small decrease in machine recovery, Figure 7.4, or increase in fruit injury, Figure 7.5, would result in a negative EPMAR. The magnitude of EYMAR increased from 1968 to 1971 so that less machine recovery or more fruit injury could be allowed before EYMAR would become negative.

6. The sensitivity to variation in machine recovery indicates that orchard modification (for mechanical harvesting) which would reduce yield an amount equivalent to a .10 decrease in machine recovery would seriously reduce the expected margins.
7. EYMAR and EPMAR can be substantially increased by an increase in harvest rate from 10 to 15 trees per hour, Figure 7.3. This indicates that orchard design, machine design, and machine management should be aimed at achieving a harvest rate of more than 10 trees per hour. About 60% of the increase in EPMAR from 10 to 15 trees per hour can be accounted for in labor savings.
8. EPMAR was negative for about 60 acres or less, Figure 7.6, but the trend of EYMAR indicates mechanical harvesting is becoming feasible for smaller acreage growers.
9. EYMAR and EPMAR were highly positive for growers with 25% higher average yields than assumed in developing the yield simulator, Figure 7.7.
10. EPMAR will increase about $3500.00 for each $1.00 reduction in assumed hourly labor cost, Figure 7.11.
11. EPMAR will increase about $12,000.00 for a $0.10 per bu increase in the piece rate paid for hand picking, Figure 7.12.

The sensitivity analysis for harvest system 4 shows:

1. The same types of relations and trends as for harvest system 3.
2. Less sensitivity to variations in the number of operators per system, Figure 7.14; the hourly cost of labor, Figure 7.23; and fruit price, Figure 7.22, than harvest system 3.
3. The same sensitivity to variations in machine recovery, Figure 7.16; fruit injury, Figure 7.17; fruit size, Figure 7.18; natural defects, Figure 7.19; and the piece rate paid for hand picking, Figure 7.24, than harvest system 3.
4. More sensitivity to variations in equipment cost, Figure 7.13; total acres, Figure 7.18; and yield, Figure 7.19; than harvest system 3.

The sensitivity and magnitude of EYMAR and EPMAR to each parameter depends on the initial combination of parameters selected. However, the initial parameter values and these sensitivity results are thought to be realistic.

7.4 Harvest Simulation Conclusions

1. Sufficiently accurate estimates of the expected value and standard deviation of planning margin for a mechanical harvest system can be obtained from HARVSIM by including 80 growers in the simulation.

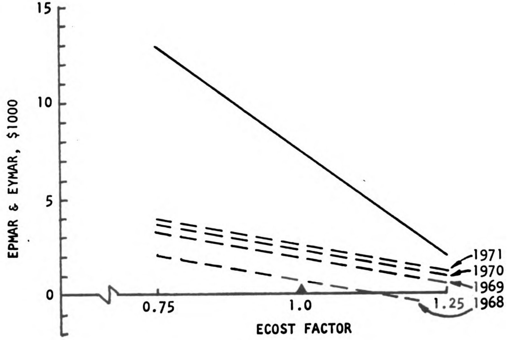

Figure 7.13 Sensitivity to Equipment Cost.

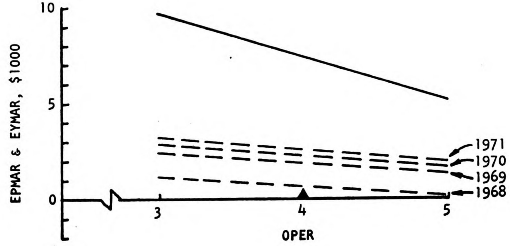

Figure 7.14 Sensitivity to Crew Size.

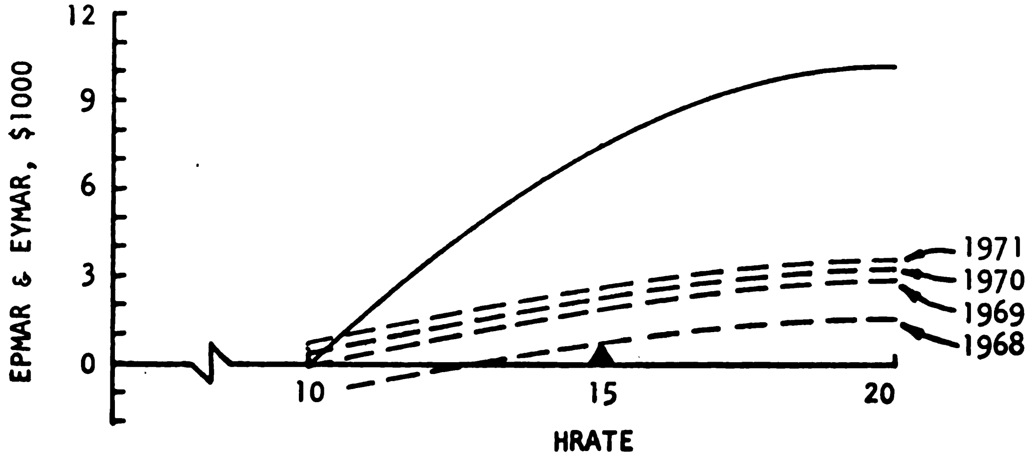

Figure 7.15 Sensitivity to Harvest Rate.

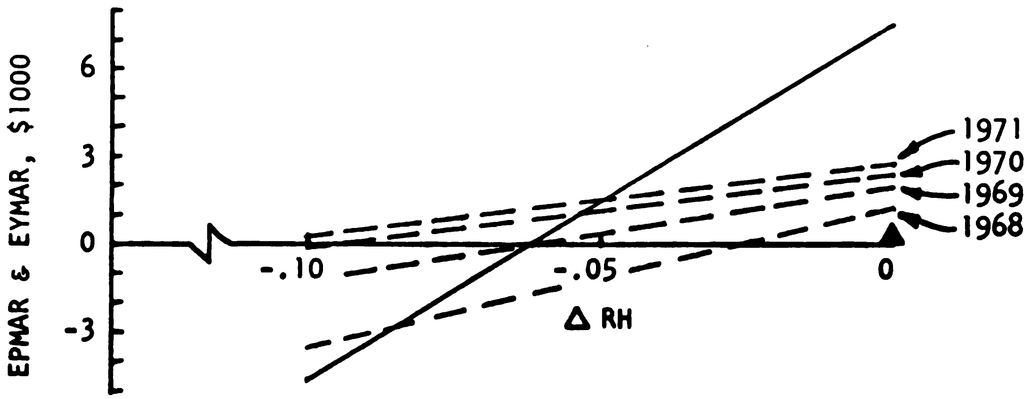

Figure 7.16 Sensitivity to Machine Recovery.

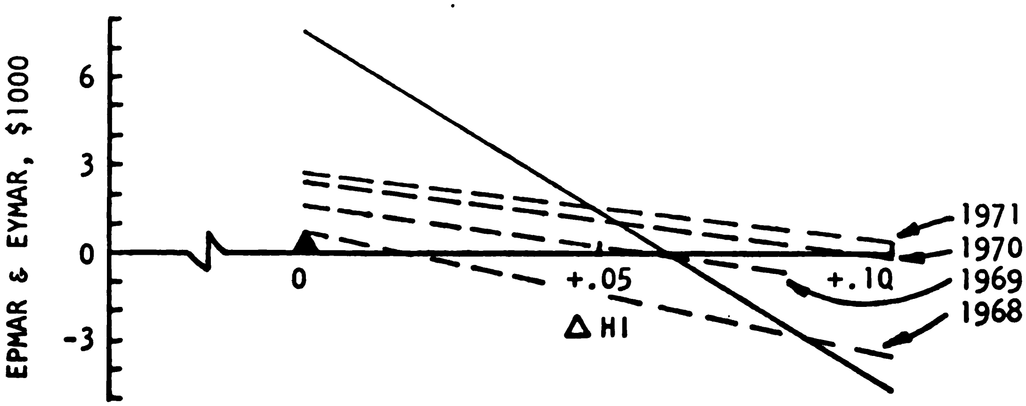

Figure 7.17 Sensitivity to Fruit Injury.

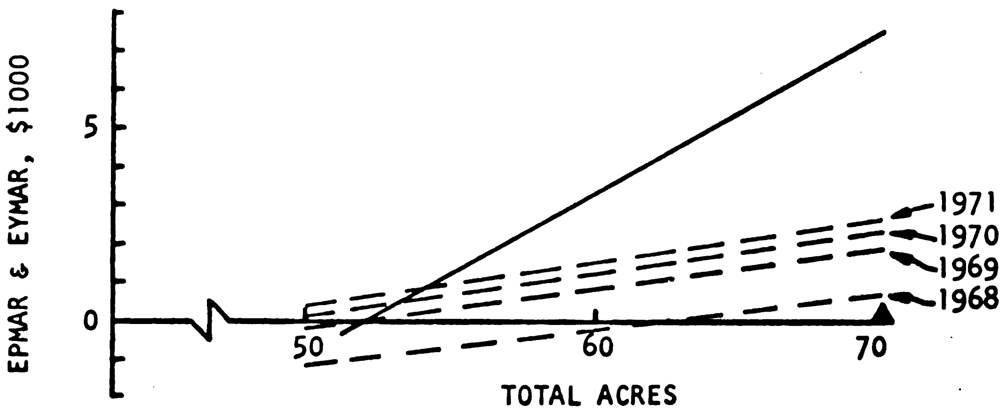

Figure 7.18 Sensitivity to Total Acreage.

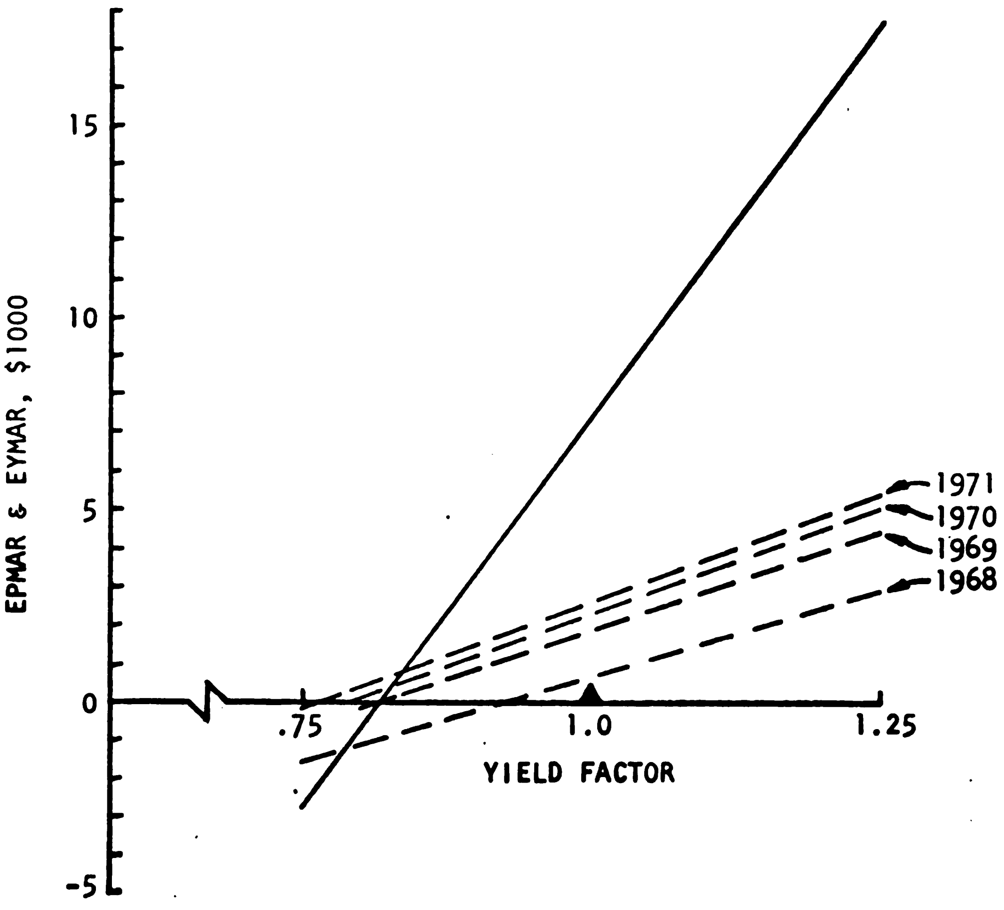

Figure 7.19 Sensitivity to Yield.

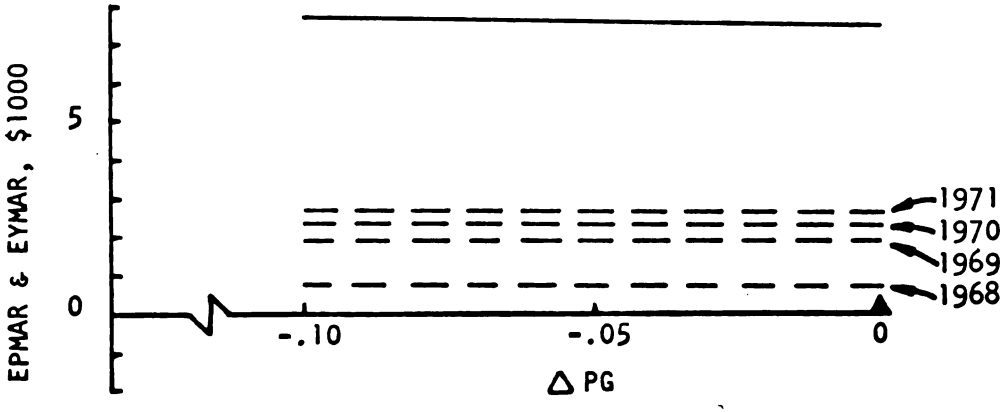

Figure 7.20 Sensitivity to Fruit Size.

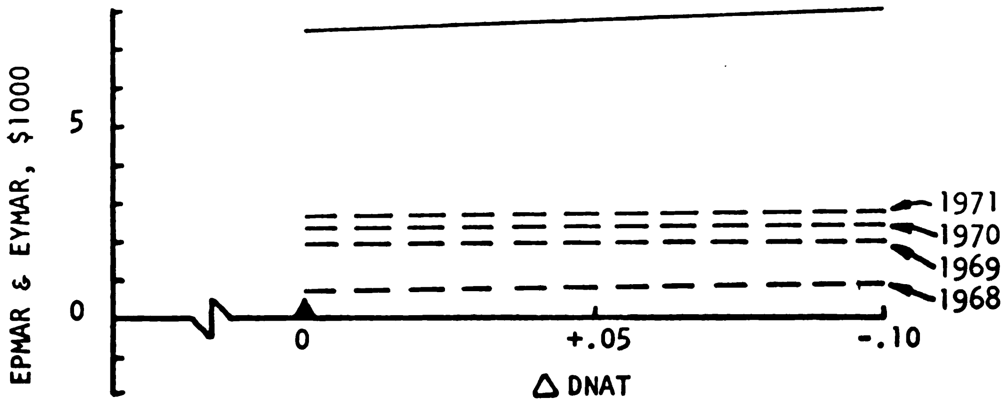

Figure 7.21 Sensitivity to Natural Defects.

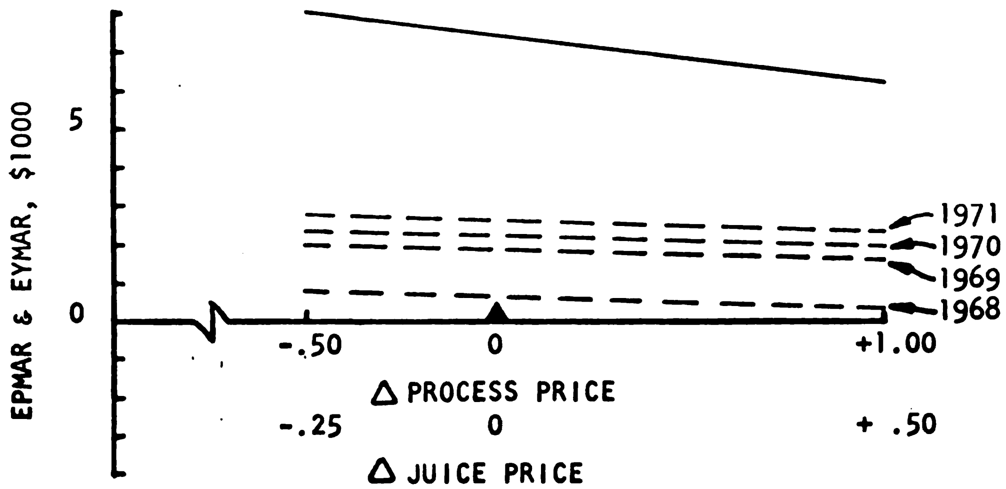

Figure 7.22 Sensitivity to Fruit Price.

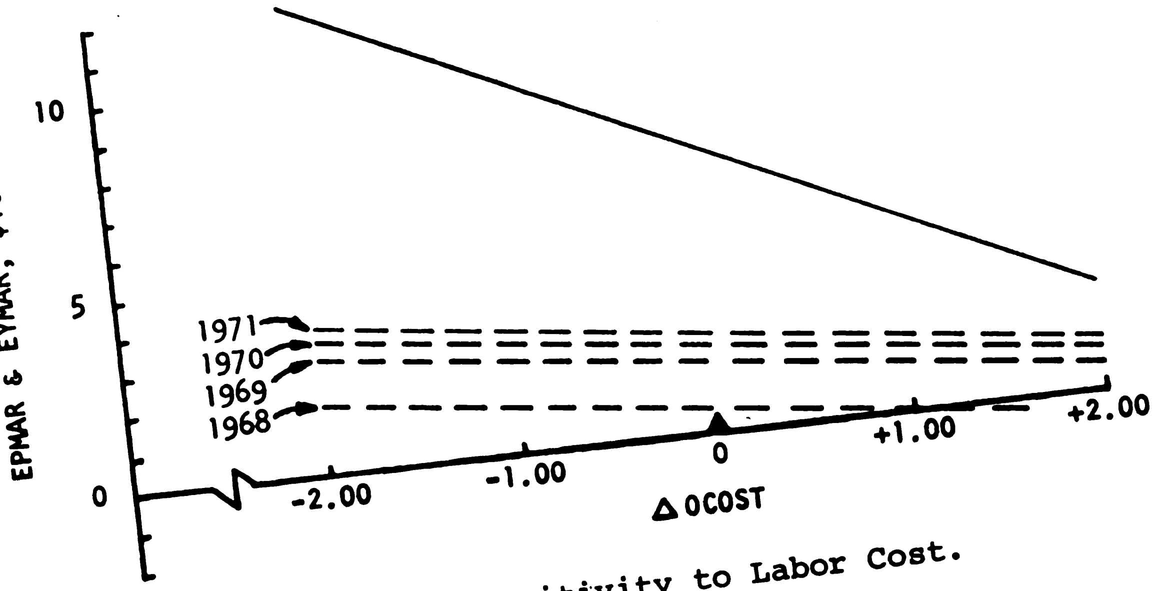

Figure 7.23 Sensitivity to Labor Cost.

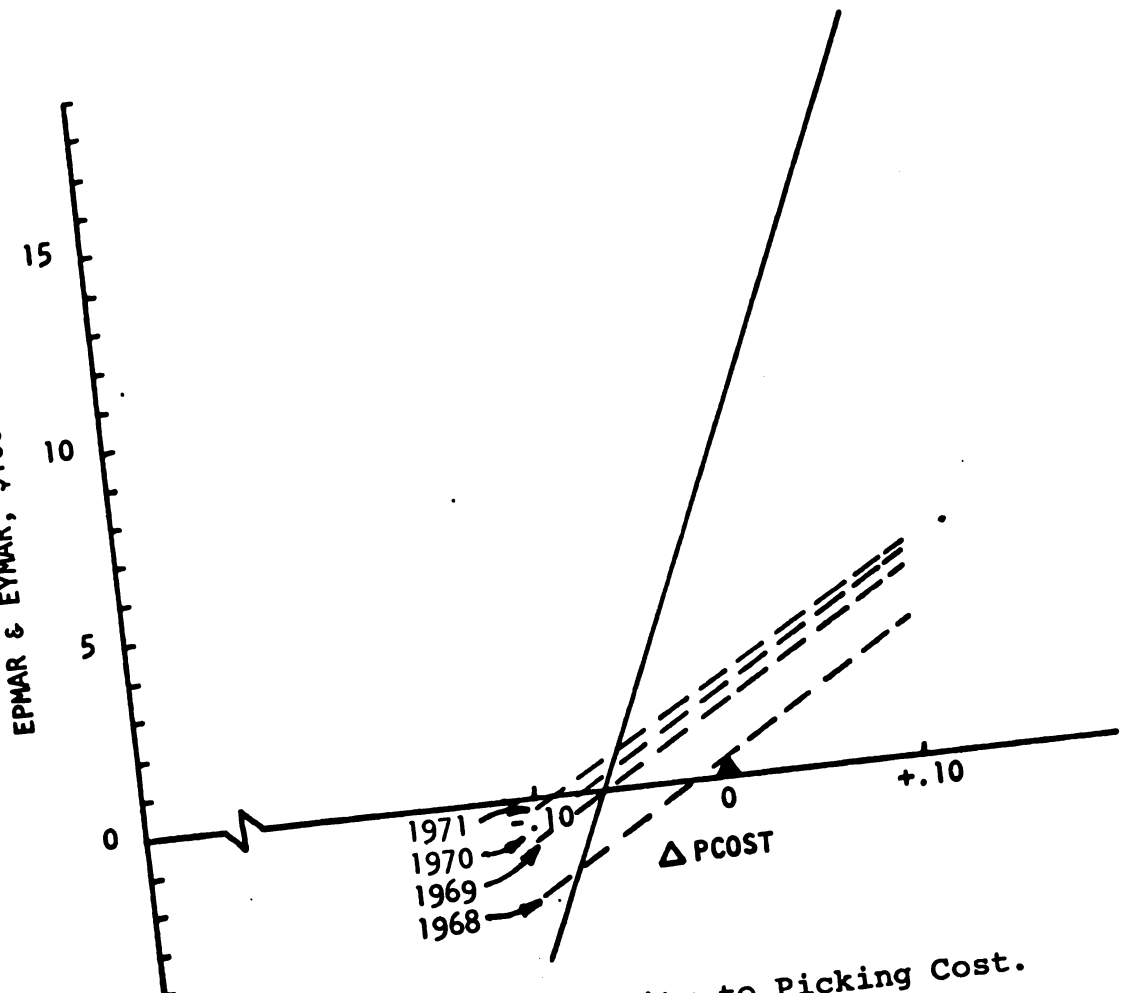

Figure 7.24 Sensitivity to Picking Cost.

2. The expected value of margin increased steadily during the assumed planning period 1968-1971.
3. The expected value for planning margin was positive for both assumed mechanical harvest systems.
4. The probability that an individual grower will experience negative margin or negative planning margin, or any other range of margins, can be estimated using the Normal Distribution and the simulation results for expected margin, standard deviation of margin, expected planning margin, and standard deviation of planning margin.
5. The probability that an individual grower had a negative planning margin was estimated at 0.05 for harvest system 3 and 0.00+ for harvest system 4.
6. The simulation and probability results for planning margin indicate that the use of either mechanical harvest system was feasible during the 1968-1971 period.
7. The sensitivity analysis shows that expected margin and expected planning margin are sensitive to all 12 parameters included in the analysis, being least sensitive to variations in fruit size and natural defects.
8. The sensitivity analysis shows that machine recovery and fruit injury are critical harvest system design parameters which, with only small undesirable

changes, can result in negative margins. Harvest rate is another important parameter in terms of its effect on margins.

9. The expected planning margin is highly sensitive to the piece rate paid for hand picking, increasing about $12,000.00 for a $0.10 increase in the piece rate.

Many additional conclusions can be drawn from the sensitivity analysis regarding tradeoffs, desirable harvester features, influence of wage rates, etc., depending on one's point-of-view.

8. APPLICATIONS OF SIMULATION RESULTS

The information generated by HARVSIM can be of maximum benefit if it is used to guide research planning, harvest system design, and the management of mechanical harvest systems.

For research planning the results generated by HARVSIM, Tables 7.3 and 7.4, the probabilities of negative margin (YMAR) and planning margin (PMAR), Table 7.5, and the sensitivity analysis are adequate for identifying feasible harvest system proposals and research areas which need initial emphasis.

A thorough understanding of the sensitivity analysis results will be beneficial for harvest system management, particularly when YMAR and PMAR are highly sensitive to changes in machine recovery, fruit injury, harvest rate, and hand picking cost.

All the above information is useful for harvest system design. However, a formalized procedure for using simulation results to select design parameter values does not presently exist. A selection criteria and procedure are proposed in the following Sections.

8.1 Criteria for Selecting Design Parameter Values

As stated in Section 1.2, present techniques for selecting the necessary or allowable values for design parameters involve computing breakeven conditions, for harvest costs or grower returns, between the conventional hand harvest method and the proposed mechanical harvest method. But, because YMAR and PMAR are normally distributed, this procedure results in parameter values which cause 50% of the growers to have negative YMAR (or PMAR) for the assumed conditions. The standard deviations for YMAR and PMAR, given in Table 7.3, suggest that YMAR and PMAR will be very negative for some growers, which is clearly undesirable.

An alternate criteria to consider is one which requires a low probability of negative PMAR. If this probability was set at 5%, parameter values would be selected so that 95% of the growers would have a positive PMAR. Table 7.5 shows that harvest system 3 would have met this criteria and harvest system 4 would have exceeded this criteria. However, the yearly results for harvest system 3 show that 74% of the growers would have experienced negative YMAR in 1968. Thus, in addition to a low probability of negative PMAR, it is necessary that a low probability of negative YMAR be achieved also.

8.2 Probability--Parameter Relations

To select parameter values based on a low probability of negative YMAR and PMAR, the relations between probability and various combinations of parameter values must be available. The results and conclusions in Chapter 7 suggest that these relations can be conveniently described in graphical form.

In Section 7.2 YMAR and PMAR were assumed to be normally distributed random variables. The relation between such variables and their cummulative probability of occurrence will plot as a straight line on normal probability paper (26). The sensitivity analysis shows that both expected margin (EYMAR) and expected planning margin (EPMAR) are related linearily to 11 of the 12 parameters. For harvest system 3, EPMAR will increase about $860.00 for each 5% decrease in equipment cost, Figure 7.1. Using this EPMAR--equipment cost relation and the standard deviation given in Table 7.3 the probability of negative PMAR can be determined for various equipment costs. If the relation between equipment cost and probability of negative PMAR is plotted on probability paper a straight line will result because: (1) EPMAR and equipment cost are linearily related; and (2) PMAR is normally distributed about EPMAR.

Program HARVSIM was used to calculate EPMAR values (based on 80 growers) for harvest system 3 assuming a range of initial equipment costs and harvest rates. The probability of negative PMAR was calcualted for each EPMAR value and the results were plotted on probability paper, Figure 8.1. The probability of negative PMAR was treated as the independent variable, equipment cost as the dependent variable, and harvest rate as a graph parameter. The results show the combinations of initial equipment cost and harvest rate (other parameters held constant) required for a given probability of negative PMAR.

In Section 8.1 it was concluded that a low probability of negative YMAR was also required. Probability--parameter graphs can be prepared for each year of the planning period using the results generated by HARVSIM. However, the year of most interest will be the last year of the planning period since it includes the most recent historical data. The results for probability of negative YMAR in 1971 are shown in Figure 8.2.

The results in Figures 8.1 and 8.2 apply when the initial assumptions on other parameters (see Chapter 7) are held constant. However, two other important design parameters, machine recovery and fruit injury, can change. To determine their affect on probability these parameters were varied, in the above simulation, for harvest rates

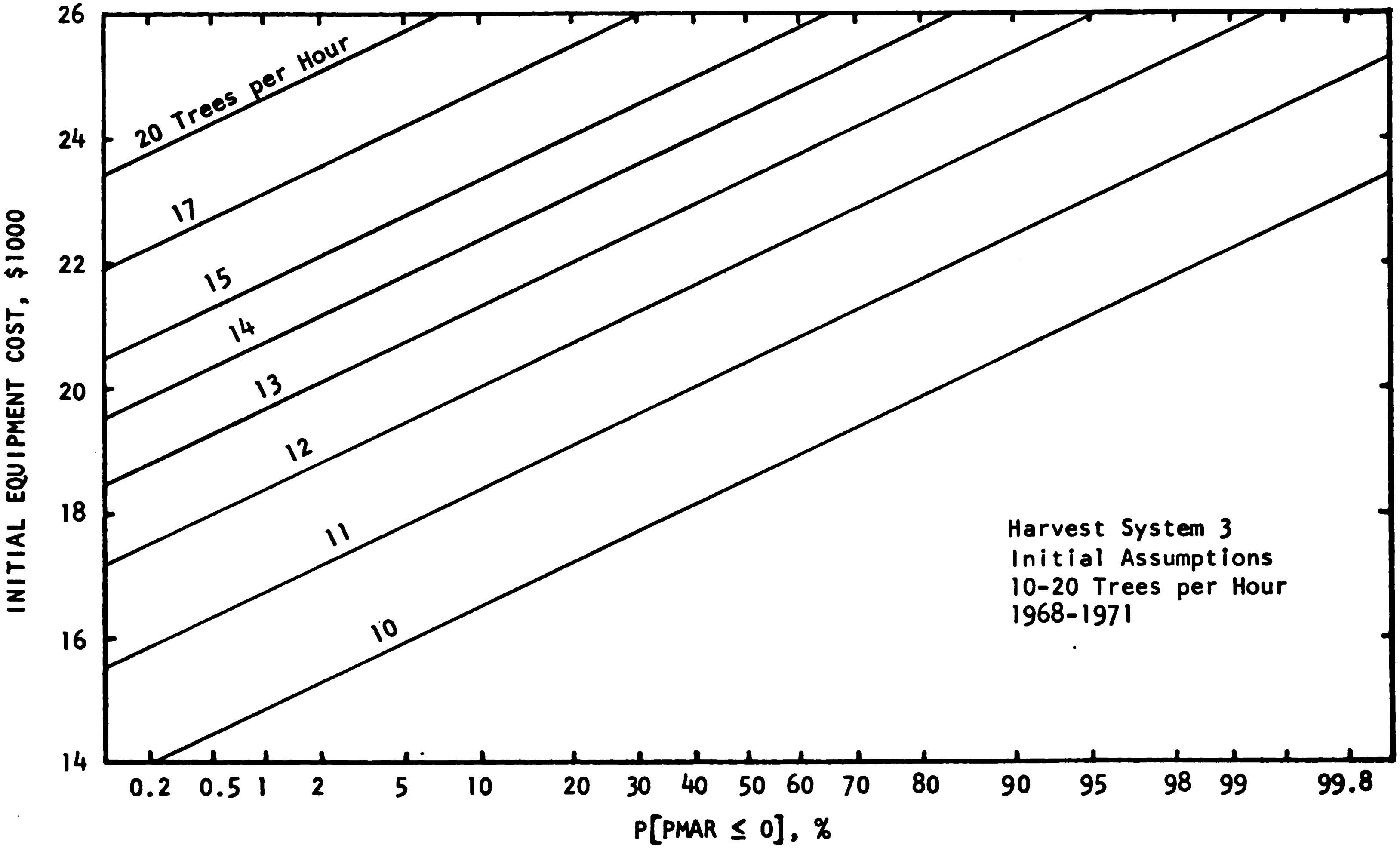

Figure 8.1 Design Parameter Values vs. Probability of Negative Planning Margin.

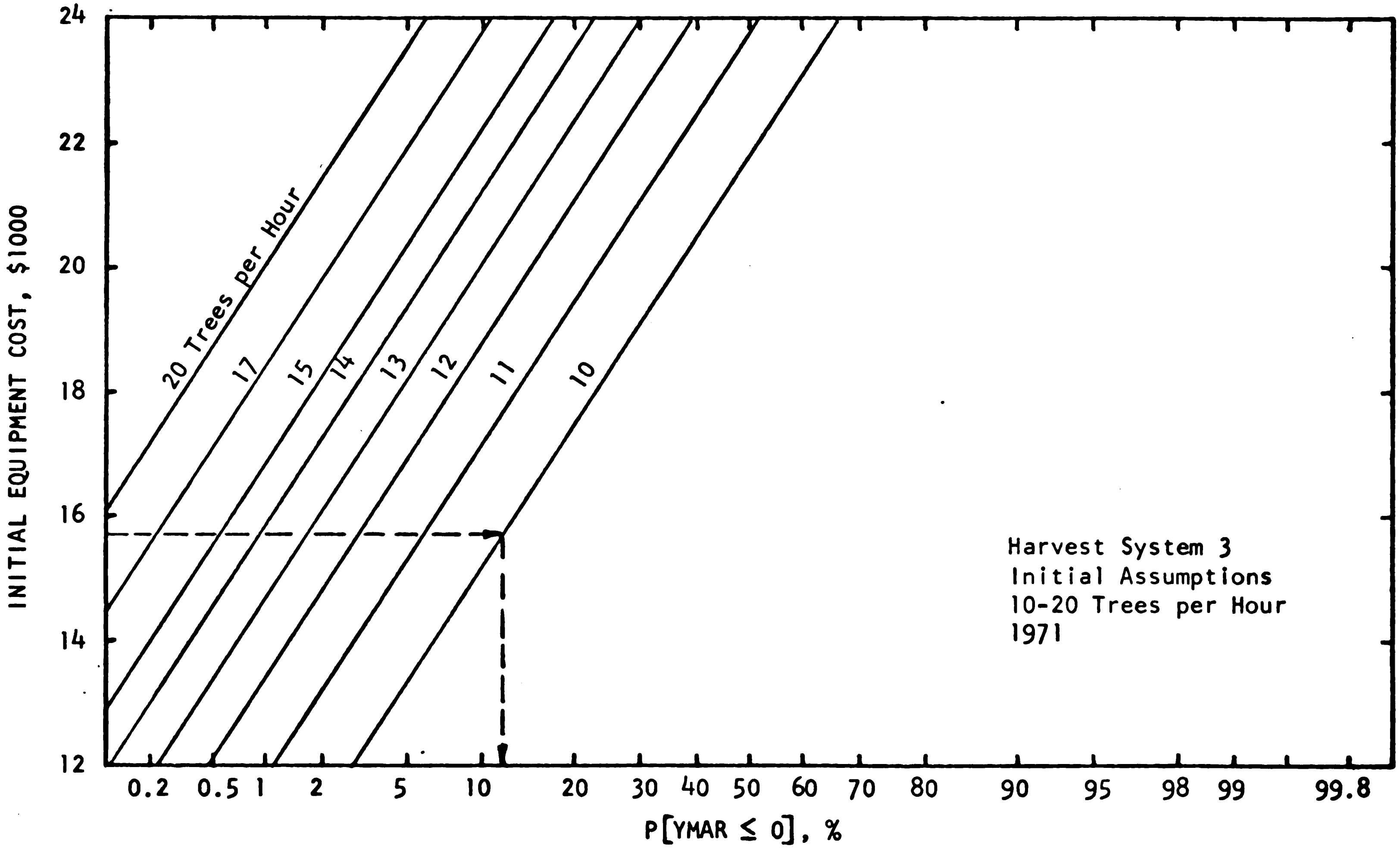

Figure 8.2 Design Parameter Values vs. Probability of Negative Margin.

of 10 and 15 trees per hour. The results, Figures 8.3 and 8.4, show the combination of initial equipment cost, harvest rate, machine recovery, and fruit injury required for a given probability of negative YMAR. Similar graphs can be prepared for the probability of negative PMAR. However, if parameter values are selected so that the probability of negative YMAR is low (e.g., 15%), the probability of negative PMAR will automatically be less than the probability of negative YMAR. The following facts provide proof for this statement: (1) PMAR is the sum of YMAR; (2) a low probability of negative YMAR means that EYMAR must be positive, thus EPMAR will be positive; (3) the standard deviation of PMAR is only slightly larger than the standard deviation of YMAR; (4) the ratio of EPMAR to the standard deviation of PMAR will always be greater than the ratio of EYMAR to the standard deviation of YMAR--thus, the probability of negative PMAR will always be less than the probability of negative YMAR.

Figures 8.3 and 8.4 again show that small changes in machine recovery and fruit injury result in large changes in YMAR. Also, the magnitude of change in probability or in initial equipment cost for a change in machine recovery or fruit injury is less at a high harvest rate than at a low harvest rate. Obviously this process could be continued until variations in all controllable or design parameters are included in similar graphs.

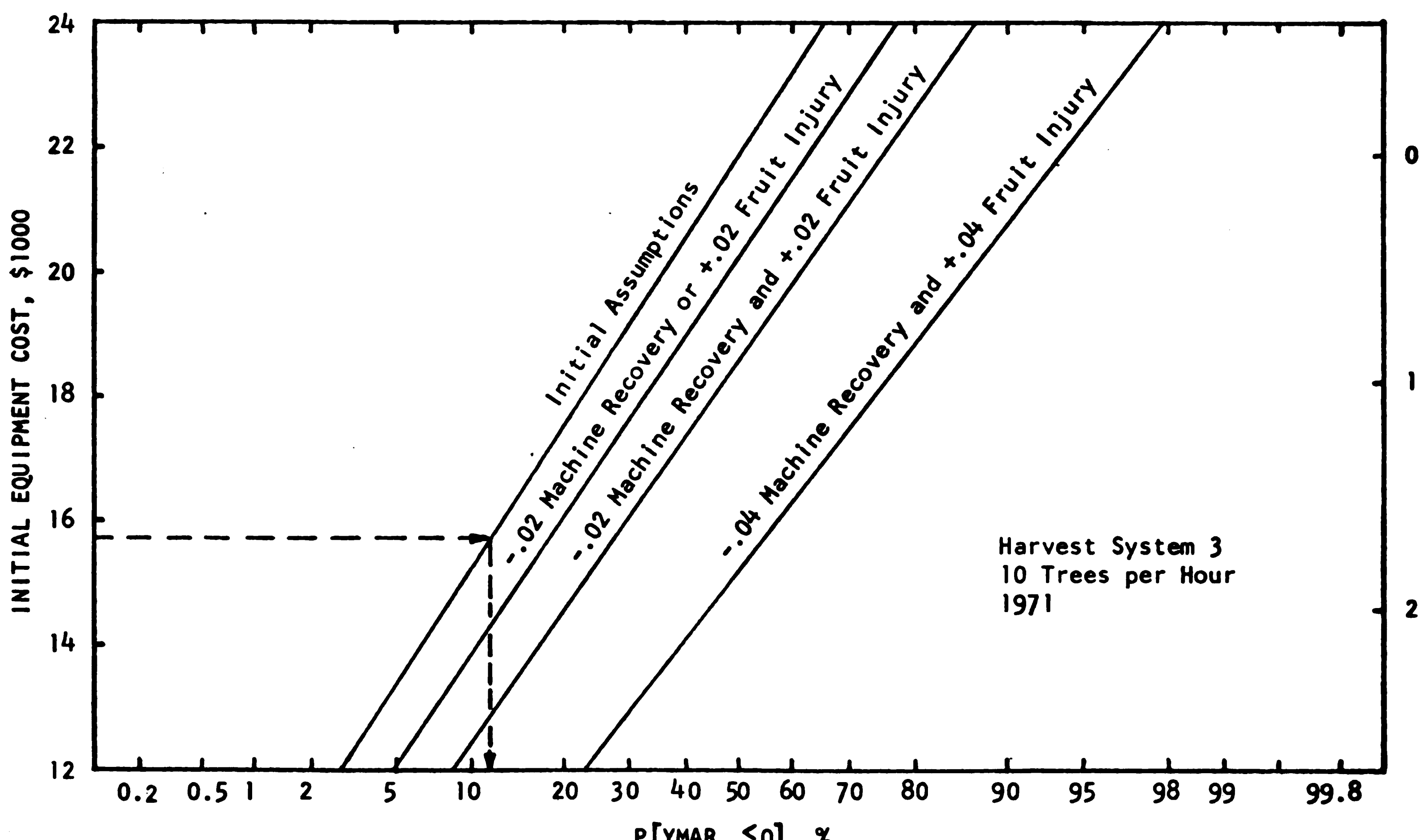

Figure 8.3 Design Parameter VAlues vs. Probability of Negative Margin.

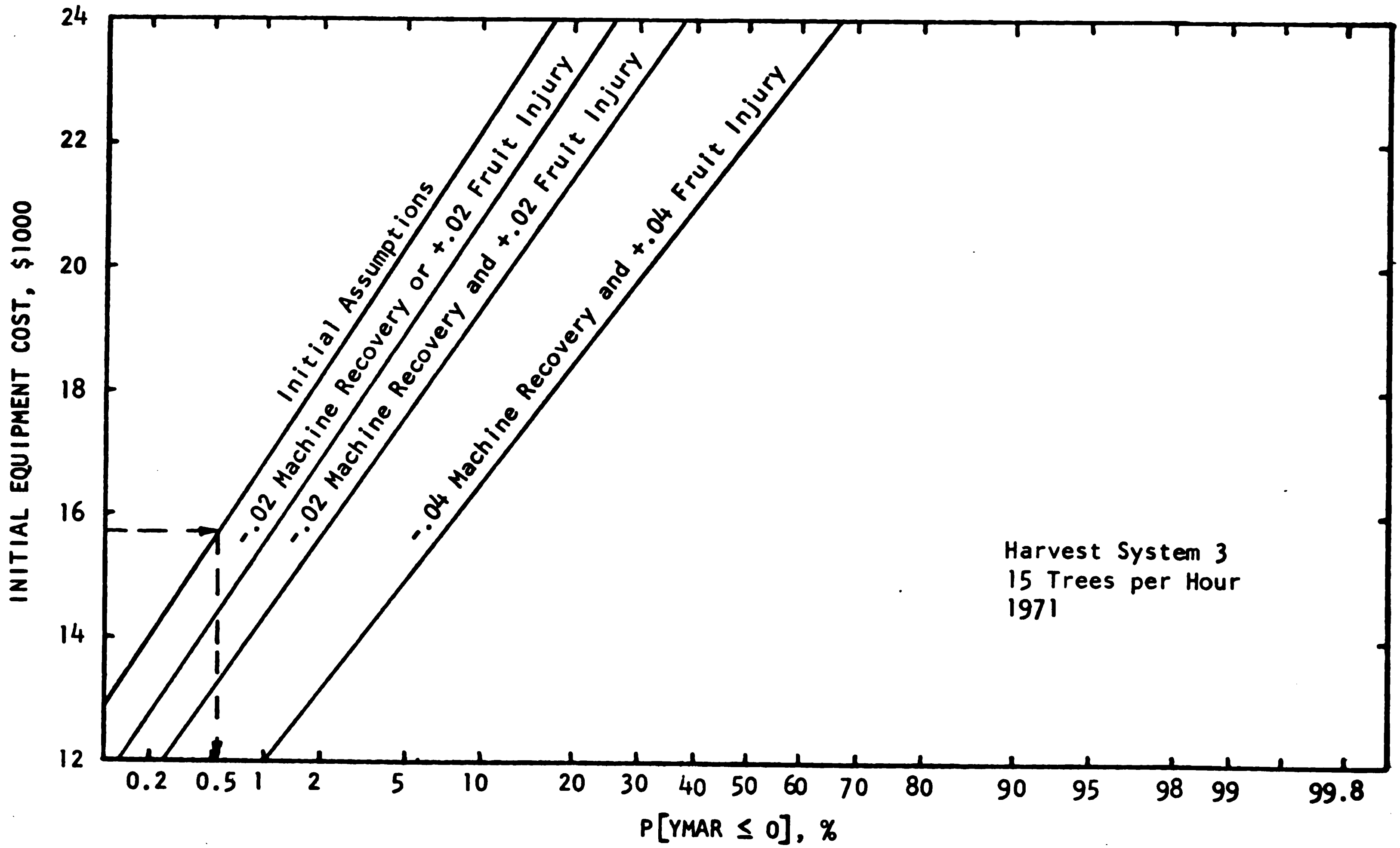

Figure 8.4 Design Parameter Values vs. Probability of Negative Margin.

8.3 Procedure for Selecting Design Parameter Values

All relations discussed in the previous section were based on historical data. In equipment design the conditions which will exist when the equipment is put into use must be anticipated. Each year of the planning period will have different conditions, thus some guesswork is required.

The trend of annual results for both mechanical harvest systems analyzed, Tables 7.3 and 7.5, indicate that a low probability of negative PMAR does not require a low probability of negative YMAR each year. However, in equipment design it seems reasonable to require a low probability of negative YMAR for conditions considered likely to occur. This suggests that parameter value selection should be based on a low probability of negative YMAR.

One approach would be to estimate the equipment cost, labor cost, and fruit values which may exist when the harvester is ready for use, then use HARVSIM to determine simulated results for one year, such as given in Figure 8.4, and select the required parameter values. For example, if the results in Figure 8.2 had been determined using estimates for 1972 and a 10% probability of negative YMAR was used as the design criteria, a mechanical harvester with a projected cost of $23,800.00 in 1972 would need to have a harvest rate equal to or greater than 17 trees per hour. Contrast this combination with a criteria of 50% probability of negative YMAR (breakeven) where the same equipment cost requires a harvest rate of only 11 trees per hour.

A second, less accurate, approach would be to use the most recent probability and design parameter relations, such as given in Figure 8.2, then estimate the required values for the design parameters so that the probability of negative YMAR is at some acceptable level (e.g., 10%). Next, use the sensitivity analysis results to determine if EYMAR will change substantially due to projected increases in equipment cost and wage rates, or possible changes in fruit values, and to select a final set of values for the design parameters. A simple example will illustrate this approach.

Suppose, using 1971 data, a proposed harvest system had the relations given in Figure 8.2. For a 10% probability of negative YMAR a mechanical harvester costing $15,200.00 in 1971 would need to have a harvest rate equal to or greater than 10 trees per hour. If wage rates and equipment costs increase by 5% for 1972, EYMAR will change by the following amounts:

EYMAR for 1971, results of simulation	$1702.00
EYMAR change for 5% hourly wage increase, Figure 7.11	-179.00
EYMAR change for 5% piece rate increase, Figure 7.12	+570.00
EYMAR change for 5% equipment cost increase, Figure 7.1	-300.00
Estimate of EYMAR for 1972	$1793.00

Fruit values were low for 1970 and 1971, Table 7.1. If fruit value should increase by $1.00 per cwt for processing apples and $0.50 per cwt for juice apples EYMAR would decrease by $600.00, Figure 7.10. Thus, the final estimate of EYMAR for 1972 would be $1193.00. This $509.00 decrease in EYMAR could be recovered by designing for a harvest rate of about 11.2 trees per hour, Figure 7.3.

In the opinion of the author, a low probability of negative YMAR (in the range of 10-20%) should be used as the primary design criteria. However, both before and after the design parameter values are selected HARVSIM should be used to determine results for historical data, such as those in Tables 7.3 and 7.5, so that the consequences of using a proposed harvest system can be more fully understood. The use of this criteria together with good estimates of future conditions should result in a very low probability of negative PMAR in actual practice.

8.4 Additional Relations

Graphs of the probability--parameter relations, such as Figures 8.1-8.4, can provide additional information. For example, since EYMAR and EPMAR are linearly related to initial equipment cost, right-hand ordinates for these variables can be added to each figure so that their values can be directly estimated. A right-hand ordinate giving EYMAR values for the 10 tree per hour line (a different EYMAR scale must be used for each line) has been added to Figure 8.3. If the initial assumptions (Section 7.1) are met for harvest system 3, the probability of negative YMAR is 12% and EYMAR is $1702.00. However, if machine recovery should decrease .04 and fruit injury increase .04 the probability of negative YMAR is 55%. The corresponding EYMAR is -$135.00, but to avoid confusion its scale is not shown.

Because YMAR is symmetrically (normally) distributed about EYMAR, a 12% probability of negative YMAR for an EYMAR of $1702.00 also implies a 12% probability that YMAR will be greater than $3404.00. Also, by symmetry, the probability of YMAR greater than $1702.00 or less than $1702.00 are both 50%.

If a grower purchased harvest system 3 in 1971 the initial cost would be $18,200.00 (due to 5% inflation per year). Figure 8.2 shows the probability of negative YMAR for that grower would be 24% if all initial assumptions were met. A harvest rate of 11.2 trees per hour would be required to achieve a 10% probability of negative YMAR. This indicates that if the same rate of inflation occurs in equipment cost and wage rates, a delay in purchasing a harvester will result in a higher level of required performance if a given probability of negative YMAR is desired.

The EYMAR and probability of negative YMAR cited for harvest system 3, at an initial equipment cost of $15,700.00, are slightly different from those given in Tables 7.3 and 7.5 for the same assumptions. The difference is due to the use of a different series of random numbers (i.e., a different sample of 80 growers). By considering 1 standard deviation of the mean of YMAR (160) it is obvious that these two simulations are reasonable samples from the same population. The difference in probability of negative YMAR is about 7% and is due almost entirely to the difference in the standard deviation of YMAR for the two simulations. This difference in probability indicates that a design criteria of less than 10% probability would not be reasonable.

8.5 Advantages, Disadvantages, Limitations

The advantages of using simulation and the proposed criteria for selecting design parameter values instead of deterministic methods may be summarized as:

1. Measures of risk are provided in addition to deterministic measures of benefit.
2. The requirement of a low probability of economic loss (i.e., a high probability of economic gain) can be used as a design criteria.
3. Use of this method should increase confidence that a proposed harvest system will be beneficial.
4. Research results should be applicable to a greater number of intended users.

The disadvantages may be summarized as:

1. More input data is required.
2. More time is required for analysis.
3. A higher design cost is incurred.
4. Computer facilities are required for analysis.
5. Design requirements are set at a higher level.

The general limitations of the present method are:

1. Not all interactions, or "real world" correlations are included in the present simulation model.
2. The method is new and untried. A few years of experience will be necessary to determine if the above advantages can be realized.
3. Care must be exercised in using simulation results which have not been validated. However, the results obtained from the simulation models designed are thought to be realistic and to provide substantially more guidance than do deterministic calculations.

9. SUMMARY AND CONCLUSIONS

Apple growers in Michigan are interested in feasible mechanical harvest methods for processing apples. If harvesting was mechanized, increased productivity would permit hourly wages to be increased and would eliminate the peak demand for harvest labor.

Many of the variables in apple production, harvesting, and marketing are of a stochastic nature. Known functional relations for the individual grower were used to design a harvest simulation model, HARVSIM, to analyze some of the benefits and consequences of proposed mechanical harvest systems. Output statistics for each proposed harvest system include the expected value and standard deviation for margin, planning margin, harvest cost per bushel, productivity, and indices for the volume of fruit in processing, juice, and windfall quality categories.

Sub-system models, required in HARVSIM, were designed for annual yield, daily windloss, daily work time lost due to rain or Sundays, and machine breakdown.

The model for annual yield generates yields via a first-order autoregression relation which uses the cummulative distribution function for annual yield and negative correlation between successive yields for a given variety.

The model for daily windloss generates average daily wind velocities via a first-order autoregression relation which uses the cummulative distribution function for average daily velocity and positive correlation between successive velocities. A derived relation between daily windloss and daily average wind velocity is used to calculate daily windloss for a given variety.

The model for daily work time lost due to rain generates daily lost time using the cummulative distribution function for daily lost time based on historical records of hourly rain observations and a no-work criteria based on amount of rain. The first Sunday each season occurs at random within the first seven days. Successive Sundays occur at seven-day intervals.

The model for machine breakdown assumes that operating time between failures is exponentially distributed.

Harvest rate--acreage relationships were determined based on the length of harvest season, beginning and ending dates for harvesting each variety, harvest rate, occurrence of lost time, and probability of completing the total acreage within the defined length of season.

Delayed harvest policies were evaluated to determine if harvested volume would change substantially under the combined affects of fruit growth and daily windloss.

For a planning period including years 1968-1971, HARVSIM was used to simulate results for 80 growers with 70 acres of standard type apple trees and two possible mechanical harvest systems. A sensitivity analysis, using variations in 12 input parameters, was conducted for both harvest systems.

Three criteria for the selection of design parameter values were examined: (1) breakeven conditions between hand and mechanical harvest methods; (2) a low probability of negative margin; and (3) a low probability of negative planning margin.

Simulation and sensitivity results were used to develop a procedure for selecting values for harvester design parameters so that a low probability of negative margin can be achieved.

Conclusions derived from this study included:

1. The models developed for annual yield and daily windloss are adequate for harvest simulation applications.
2. The model developed for daily work time lost due to rain agreed closely with grower opinion.
3. For a 90% probability of completing the harvesting of 70 acres of standard type trees in a six-week season, a harvest rate of 10 trees per hour is required. This is based on six working days per week and a maximum of eight hours of work per day. The effect of work time

lost due to Sundays, rain, and machine breakdown is included. A change in total acreage requires a proportionate change in harvest rate.

4. Simulation results for a general policy of delaying the start of harvest indicates that the harvested volume will decrease slightly, except under conditions of sustained rapid fruit growth.
5. Simulation results indicate that the expected margin for two assumed mechanical harvest systems increased steadily and the probability of negative margin decreased steadily during the period 1968-1971.
6. Sensitivity analysis indicates that small variations in harvest rate, machine recovery, fruit injury, and hand picking cost cause large variations in margin planning margin.
7. An important part of the simulation model is the inclusion of negative correlation between successive yields. This feature adds realism, and when expected planning margin is positive, the probability of negative planning margin is less than would result if successive yields were independent.
8. A low probability of negative margin (in the range of 10-20%) is proposed as a criteria for selecting design parameter values for mechanical harvest systems.

Compared to the commonly used breakeven criteria, this criteria will provide a higher level of abundance that a proposed harvest system will be of economic benefit.

9. Relations between the probability of negative margin and various combinations of design parameter values can be easily described by graphical methods.

10. RECOMMENDATIONS

1. HARVSIM and the proposed procedure for selecting design parameter values should be regarded as a first attempt at applying simulation techniques to mechanical harvesting research planning, system evaluation, system design, and system management. Refinements and different approaches should undoubtedly be considered.
2. Additional "real world" inter-relationships should be considered for inclusion in HARVSIM. For example, relations between fruit price and annual yield, daily windloss and number of days since reaching maturity, fruit growth and percent of crop with acceptable size for processing, processor operation and harvest method (fruit price may be affected), may improve the realism and usefulness of the model.
3. Detailed data on machine recovery and fruit injury should be obtained from experimental harvesters to determine if these parameters may be considered as constants or must be considered as random variables.
4. A simulation model should be designed for analyzing the mechanical harvesting of apples for fresh market utilization. The model HARVSIM is a logical starting point for a fresh market model.

5. Researchers working on the development of mechanical harvest systems for fruit and vegetable crops should make use of simulation and the harvest system design procedure proposed in this study. The major reasons for this recommendation are that by using these techniques:

    a. Harvest rate--acreage relationships can be accurately determined.

    b. Unknown relations, such as the windloss-wind velocity relation, can be inferred from available data.

    c. Theoretical differences between various policies can be determined.

    d. Standard deviations for margin, and other useful measures of goodness, can be determined.

    e. Harvest systems can be designed and evaluated using a criteria of low risk of economic loss.

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