Economic Analysis of Robotic Citrus Harvesting in Florida

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ABSTRACT

COSTS were formulated for robotic citrus harvesting in Florida. Nineteen factors were identified which affected harvest costs. A nominal analysis state was established by making best estimates for all factors. These included a purchase price for a multiple arm harvester of $25,000/arm, an average pick cycle time of 3 s, and a harvest inefficiency of 15%. Robotic harvest cost resulting from the nominal state was $2.15 per 41 kg box. This was 50% greater than the average 1983-84 Florida hand harvest cost (Hooks, 1986). It was found that robotic harvest cost was affected most by harvest inefficiency followed by harvester purchase price, average pick cycle time, and harvester repair expense. It was concluded that research and development of robotic harvesting technology should continue and should concentrate on the following areas: (a) harvest inefficiency, (b) purchase price, (c) harvester reliability, and (d) modifications in the work environment that would improve the performance of robotic harvesters and to determine how these modifications could be implemented.

INTRODUCTION

Recently, the technical feasibility of picking tree-fruit robotically has been demonstrated. Single arm systems have been developed in France (Gran d'Esnon, 1985) and the U.S. (Harrell et al., 1985) that pick fruit, located by machine vision, with simple three-degree-of-freedom arms. Second generation arms are currently being tested in both countries to evaluate this technology under actual production conditions.

For robotic tree-fruit harvesting to succeed, the developers of these harvesters must take into account constraints imposed by both the work and economic environments in which the systems will be operated. Grove and orchard work environments have been well characterized for mechanical harvesting systems (O'Brien et al., 1983, Brown et al., 1971, and Tennes and Levin, 1972). Likewise, the economic environment has been well characterized for mechanical tree-fruit harvesting systems (Rothelli, 1973 and Whitney, 1971). However, the unique nature of robotic harvesting requires unique design data, much of which is currently unavailable. Field evaluation of the second generation -single arm systems will help characterize the aspects of the work environment unique to robotic harvesting. Specific economic studies are needed to identify and quantify the unique economic factors.

One of the first attempts to characterize robotic tree-fruit harvesting economics was by Pesja and Orrock (1983). In this work, the economics of a hypothetical two arm citrus harvesting system was considered. At the time of the Pejsa and Orrock study, technical requirements for picking tree-fruit robotically had not been well established. The lack of this information required making many assumptions concerning purchase price, operation, and performance of the robotic harvester. In addition, the influence of these factors on harvesting costs were not considered.

The goal of this paper is to establish economic design priorities for robotic citrus harvesting systems. This is done by developing a cost formulation of a robotic citrus harvesting operation. The cost formulation is based on projected operating characteristics of a multiple arm harvester designed for Florida groves. The formulation is used to quantify the influence of cost variables. Economic design criteria are established based on the most influential cost variables.

HARVESTER DESIGN AND OPERATION

One design concept considered for a multiple arm robotic citrus harvester utilizes a self-propelled gantry structure which straddles a row of trees. Attached to the harvester are multiple three-degree-of-freedom picking arms. A diagram of a typical arm is shown in Fig. 1.

Picking arms are hydraulically actuated. Each arm pivots in a Hooke-Joint base about intersecting and perpendicular axes. A prismatic link, mounted in the Hooke-Joint, provides motion in and out of a citrus canopy. Arm actuation is accomplished with two rotary actuators and a hydraulic motor. A rack and pinion drive is used to obtain linear motion from the hydraulic motor. High performance servo valves, controlling actuator flow, are used to achieve the dynamic performance required to pick moving fruit.

Attached to the end of the sliding link is a rotating lip picking mechanism. A solid state color video camera, range sensor, and stroboscopic lamp are incorporated into the picking mechanism for fruit identification and location. Color machine vision enables the picking arm to rapidly distinguish between the various hues present in a citrus canopy.

When a fruit is detected by the vision system, angular velocities of the two rotational joints are regulated, maintaining the targeted fruit's projection in the center of the image plane. The sliding link is actuated, extending the picking mechanism towards the targeted fruit until it is close enough to detach the fruit from the canopy. Once detached, the sliding link is retracted from the canopy and the fruit dropped into a fruit collection

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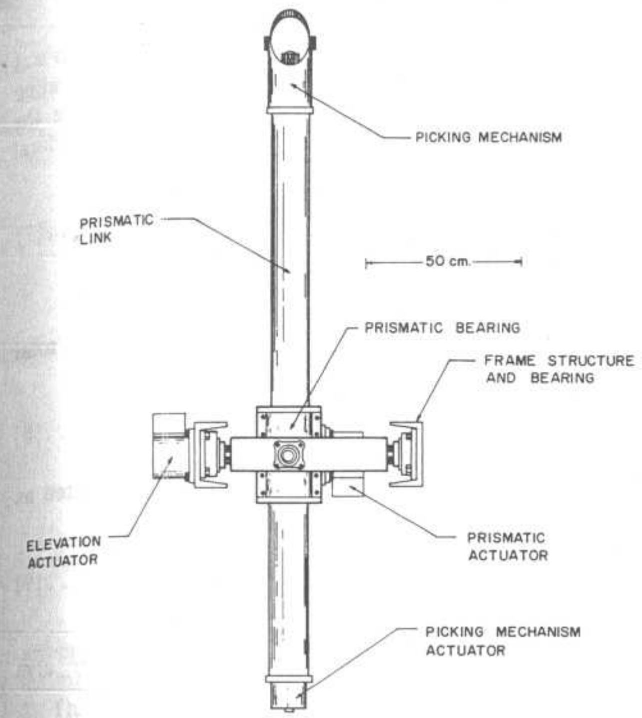

Fig. 1—Diagram of citrus picking arm.

system. Picking arms are designed to complete a worst case pick cycle (i.e., a targeted fruit at the extreme edge of the arm's workspace) in 1 s.

As the self-guided gantry vehicle moves along a row of trees, fruit is picked and dropped into the fruit collection system. The harvested fruit is conveyed to a trailer towed behind the harvester. When full, the trailer is automatically decoupled from the harvester and grove personnel notified. A grove worker attaches an empty trailer to the harvester and tows the full one to the roadside where it is emptied into a fruit hauling truck. A storage bin on the harvester allows operation to continue during brief periods when no trailer is connected. The harvester stops when it reaches the end of the row and must be repositioned by grove personnel before the harvesting operation can continue. When the harvesting operation is complete, the harvester is transported to the next grove to be harvested. Lights on the harvester allow operation during darkness.

HARVEST COST FORMULATION

The cost formulation developed below follows a cost formulation for mechanical citrus harvesting systems presented by Rothelli (1973). Modifications were made to account for the unique aspects of a robotic harvesting operation. It was assumed in this formulation that there would be no change in fruit quality nor reduction in future yields as a result of robotic harvesting and there would be no gleaning of fruit left on the tree by the harvester. Harvest costs were formulated on a per arm basis as the sum of fixed, operating, overhead, and unpicked fruit costs. A per arm approach was used in order for the analysis to be reasonably independent of the number of arms on a given harvesting system. Harvesting was defined in this analysis as the act of removing fruit from the tree, hauling fruit from grove interior to roadside, and loading fruit into trucks for transportation to processing plant or packinghouse.

Fixed costs included depreciation, interest, taxes and insurance, and sheltering expense. The straight line method was used to depreciate equipment. Interest, taxes and insurance, and sheltering expense were computed as percentages of the average annual value of the harvesting system (harvester purchase price/2). The purchase price of the harvester was divided into arm and support equipment purchase prices. The arm purchase price covered mechanical and electronic components incorporated into a single harvesting arm. Support equipment purchase price covered costs of all other equipment needed to implement a robotic harvester as previously described. This included the self-guided gantry structure, power units, fruit collection system, grove vehicles, and intragrove transportation vehicles. The support equipment purchase price was the total estimated cost for these items divided by the number of arms on the harvester. Fixed cost, on a per arm basis, was formulated as follows:

$$FC = (APP + SEPP)*[(TI + IR + SE)/2 + (1/DL)] \ldots [1]$$

where
FC = harvesting operation fixed costs, \$/season
APP = arm purchase price, \$
SEPP = support equipment purchase price, \$
TI = annual taxes and insurance rate, decimal fraction
IR = interest rate, decimal fraction
SE = annual shelter expense, decimal fraction
DL = depreciation life, years.

Robotic harvester operating cost was calculated as the sum of energy cost, repair and maintenance cost, field labor cost and grove conditioning expense. Harvester energy cost was the annual expenditure for fuel to operate the robotic harvester and support vehicles. On a per arm basis, energy cost was calculated with:

$$EC = OT*HPR*UEC \ldots \ldots [2]$$

where
EC = seasonal energy cost, \$
OT = harvester operating time per season, h
HPR = per arm harvester power requirments, kW
UEC = unit energy cost, \$/kW·h.

Harvester repair and maintenance expenses were separated into arm and support equipment repair and maintenance costs. Arm repair cost was calculated as a percent of arm purchase price per one million pick cycles. Support equipment repair and maintenance costs were determined as a percent of support equipment purchase price per 1000 h of operation. Annual harvester repair and maintenance cost was calculated on a per arm basis with the following:

$$RMC = OT*[(0.0036*ARR*APP/PCT) + (SERR*SEPP/1000)] \ldots \ldots [3]$$

where
RMC = harvester repair and maintenance cost, \$/season
ARR = arm repair rate, decimal fraction of APP/one million pick cycles
PCT = average pick cycle time, s/fruit
SERR = support equipment repair rate, decimal fraction of SEPP/1000 h of operation.

Grove labor costs were annual wages and fringe benefits paid to grove personnel required for harvester operation. It was calculated on a per arm basis as follows:

$$LC = OT*LR \quad \ldots\ldots [4]$$

where

LC = harvester grove labor expenses, \$/season
LR = composite harvester labor rate, \$/(arm*h).

Grove conditioning was the expense to maintain groves in a condition suitable for robotic harvesting systems. This expense was calculated as follows:

$$GCC = (OT*GCR*3600)/[FPH*FPB*PCT*(1 - HI)] \quad \ldots\ldots [5]$$

where

GCC = grove conditioning expense, \$/season
GCR = grove conditioning rate, \$/ha
FPH = amount of fruit per ha, boxes
FPB = number of fruit per box
HI = harvester inefficiency, decimal fraction.

Harvester inefficiency represents that portion of fruit which was not picked by the robotic harvesting system. It must be included in equation [5] to account for the additional grove area required to harvest a given amount of fruit. Harvest inefficiency must also be accounted for in an unpicked fruit expense since 100% fruit removal is assumed to be achieved through manual harvesting. The unpicked fruit expense was formulated as follows:

$$UPF = (OT*3600*OTV)*[HI/(1 - HI)]/(PCT*FPB) \quad \ldots\ldots [6]$$

where

UPF = unpicked fruit expense, \$/season
OTV = on-tree-value of fruit, \$/box.

On-tree-value is the price the grower is paid for his fruit when delivered to the packing house or processing plant minus the cost to harvest and transport that fruit. The unpicked fruit expense can be thought of as money which must be reimbursed to the grower by the robotic harvesting operation for fruit left in the groves.

The last cost category considered in this analysis was overhead expense. Overhead represented administration and management costs associated with operating the robotic harvester. It was calculated as a percent of total operating costs as shown below:

$$OHC = OHR*OC \quad \ldots\ldots [7]$$

where

OHC = overhead cost, \$/season
OHR = overhead rate, decimal fraction of total operating costs.

$$OC = EC + RMC + LC + GCC \quad \ldots\ldots [8]$$

Total annual robotic harvest costs were calculated as the sum of the above factors or:

$$AHC = FC + OC + UPF + OHC \quad \ldots\ldots [9]$$

where

AHC = annual robotic harvest cost, \$ per arm basis.

A per box harvest cost was obtained with the following equation:

$$PBC = AHC*PCT*FPB/(OT*3600) \quad \ldots\ldots [10]$$

where PBC is the per box harvest cost in dollars.

HARVEST COST ANALYSIS

Harvest cost sensitivities and harvest cost estimates are developed in this section. First, estimates are made for the 19 analysis variables identified in the cost formulation. These estimates are based on projected harvester purchase price and operational characteristics, and Florida citrus production statistics. A sensitivity study is performed on the cost formulation, quantifying the influence of analysis variables on harvesting cost. Finally, harvest costs are estimated as functions of the most influential analysis variables.

Nominal Analysis State

Nineteen analysis variables were identified that

TABLE 1. NOMINAL ANALYSIS STATE ESTIMATES.

Variable name	Description	Nominal value
APP	Arm purchase price	\$15,000
ARR	Arm repair rate	10% (of APP/one million pick cycles)
DL	Depreciation life	7 years
FPB	Fruit per box	180
FPH	Fruit per hectare	544
GCR	Grove conditioning rate	\$75/hectare
HI	Harvest inefficiency	15%
HPR	Harvester power requrement	4.0 kW (per arm basis)
IR	Interest rate	15% (of average annual value)
LR	Labor rate	\$0.70/arm*h
OHR	Overhead rate	15% (of average annual value)
OT	Operating time	2000 h/season
OTV	On-tree-value	\$5.00/box
PCT	Average pick cycle time	3 seconds
SE	Shelter expense rate	1% (of average annual value)
SEPP	Support equipment purchase price	\$10,000 (per arm basis)
SERR	Support equipment repair rate	10% (of SEPP/1000 h)
TI	Taxes and insurance rate	1.5% (of average annual value)
UEC	Unit energy cost	\$0.07/kWh

TABLE 2. ITEMIZATION AND PRICING OF ARM COMPONENTS.

Component	Quantity	Unit price $	Total price $
Rack and pinion for slider	1	100	100
Hydraulic motor for slider	1	500	500
Servo valve for slider	1	400	400
Hooke-Joint actuators	2	500	1,000
Hooke-Joint servo valves	2	750	1,500
Picking Mechanism motor	1	250	250
Strobe lamp	1	250	250
Color camera and lens	1	500	500
Range sensor	1	250	250
Cable and hose set	1	500	500
Steel, bearings, and bushings	1	1,000	1,000
Position-velocity sensor set	1	400	400
Image acquisition hardware	1	1,000	1,000
Control computer	1	3,000	3,000
Servo valve electronics	3	100	300
Labor for assembly	1 man-week	1,000	1,000
		Subtotal	$11,950
		25% profit margin	$2,988
		Total purchasing price	$14,938

affected robotic harvest costs. These variables and their estimated values (nominal estimates) are listed in Table 1. The set of estimates in Table 1 is referred to as the nominal analysis state. A description of how the nominal analysis state was obtained follows.

The purchase price for harvesting arms was estimated by itemizing arm components, pricing these components when purchased in production quantities, adding $1000 for arm assembly costs, and allowing a 25% profit for the arm manufacturer (Table 2). This resulted in an arm purchase price of approximately $15,000. Purchase price estimates for the support equipment were obtained in a similar manner. Support equipment thought to be required were itemized, sized, and priced based on a 10 arm harvesting system (Table 3). Total purchase price for this equipment was projected at $100,000. This resulted in an estimated purchase price for support equipment on a per arm basis of $10,000.

Harvester performance was quantified with three analysis variables: operating time per season, average pick cycle time, and harvester inefficiency. It was assumed that harvester could operate 20 weeks of 100 h each per season for a total of 2000 h. Harvesting arms were designed to complete the worst case pick cycle in 1 s. However, to account for periods when no fruit were in the range of a picking arm, an average pick cycle time of 3 s was used. A 15% harvester inefficiency was estimated. This estimate was based on citrus fruiting characteristic data presented by Brown et al. (1971) and from observations by Schertz and Brown (1968) on the visibility of fruit in a citrus canopy.

TABLE 3. ITEMIZATION AND ESTIMATED PURCHASE PRICE FOR HARVESTER SUPPORT EQUIPMENT (BASED ON A 10 ARM HARVESTER).

Item		Purchase price, $
Gantry support structure		10,000
Half-track		20,000
Diesel engine		4,000
Hydraulic power unit		8,000
Electrical power unit		5,000
Harvester control computer		15,000
Guidance control computer		5,000
Fruit collection system		4,000
Fruit trailers		2,000
Grove vehicle		10,000
Intragrove transportation vehicle		17,000
	Total	100,000
	Per arm basis	10,000

To maintain an acceptable harvester efficiency from season to season, it was assumed that annual grove conditioning, specific for a robotic harvesting operation, would be required. This conditioning could include tree hedging, topping and skirting, and maintaining clean grove aisles for harvesting equipment. The expense for annual grove conditioning was estimated at $75/ha.

Estimates for arm repair costs were based on the quoted design life of arm components and their repair or replacement cost after design life (Table 4). Servo valves and rotary actuators were assumed to be rebuilt at the end of their design life. Other components were assumed to be replaced. All electronic components were assumed to last the life of the harvester. Picking mechanism components were assumed to need replacement after 10 million pick cycles due to accidents. Repair labor expense of $250 per 1 million pick cycles was assumed. Taking into account the above factors, arm repair rate was estimated to be 9% of the original arm purchase price per 1 million pick cycles. This rate was increased 1 percentage point to include routine maintenance expenses. Thus, arm repair and maintenance rate was estimated to be 10% of arm purchase price per 1 million pick cycles. For harvester support equipment, it was assumed that repair and maintenance expenses would be similar to that of a self-propelled combine which has been documented at 10% of purchase price per 1000 h of operation (Richey and Hunt, 1971).

Average power requirements for arm operation were projected at 2.3 kW. This was the power delivered to each arm by the hydraulic power unit. For the support equipment, power requirements were estimated at 1.7 kW times the number of arms mounted on the harvester. This included power for the harvester's prime mover, electric power unit, and support vehicles. Total per arm harvester power requirements were therefore projected at 4.0 kW. A unit energy cost of $0.07/kW·h. was used.

An estimate for the grove labor rate was made based on a projection that three manual tasks would be required to support the robotic harvesting operation.

TABLE 4. ARM REPAIR ANALYSIS.

Component	Total purchase price, $	Estimated life MPC	% of PP	Rebuild cost, % of PP/MPC	$/MPC
Rack and pinion for slider	100	2.5	100	40	40
Hydraulic motor for slider	500	2.4	100	21	105
Servo valve for slider	400	10	50	5	20
Hooke-Joint actuators (2)	1000	10	50	5	50
Hooke-Joint servo valves (2)	1500	10	50	5	75
Picking Mechanism motor	250	2.4	100	21	53
Strobe lamp	250	10	100	10	25
Color camera and lens	500	10	100	10	50
Range sensor	250	10	100	10	25
Cable and hose set	500	5	100	20	100
Steel, bearings, and bushings	1000	2.5	100	40	400
Position-velocity sensor set	400	2.5	100	40	160
Labor for repair	—	—	—	—	250
				Repair costs, $/MPC	$1,353
				Repair costs, % of PP/MPC	9%

PP – Purchase Price MPC – Millon Pick Cycles

These were: (a) roadsiding the fruit, (b) machine supervision, and (c) grove servicing of the harvester. Roadsiding was the act of transporting picked fruit from grove interior to roadside for transportation to a processing plant or packing house. Machine supervision included operations such as harvester setup, turning harvesters around at the end of rows, operational checks, minor maintenance, and intragrove transportation. Compared to roadsiding, this required a higher level of technical expertise. Grove servicing of harvesters included such tasks as emergency grove repair, routine servicing, and harvester adjustments. This required the highest level of technical expertise. Payscales for these tasks (including payroll taxes and fringe benefits) were assigned values of $7.50/h for a roadsider, $12/h for a machine supervisor, and $20/h for a grove service technician. A composite grove labor rate of $0.70/arm*h was estimated based on assumed arm capacity of each task (the number of arms that could be supported by a worker performing one of the defined tasks).

Financial analysis variables were depreciation life, property taxes and insurance rate, shelter expense rate, interest rate, and overhead rate. A depreciation life of 7 years was assumed for all equipment. The property tax and insurance rate was assumed at 1.5% and the shelter expense rate at 1.0% of the average annual value of the harvesting system. An interest rate of 15% was used for the capital investment charge. An overhead rate of 15% of total operating expenses was used.

Citrus production analysis variables were fruit per box, fruit production/ha, and on-tree-value. The number of fruit per box used was 180. This figure was based on a 41 kg field box and an average fruit mass of 230 g (Coppock et al., 1969). Estimates for fruit production/ha (544 boxes/ha) and on-tree-value ($5.00/box) were obtained from the Florida Crop and Livestock Reporting Service (Anon., 1985). These figures were composite averages for all Florida round oranges.

The cost formulation equations were solved for the nominal analysis state given in Table 1. The results (on a per arm basis) are summarized in Table 5. In this analysis, volume of fruit harvested per season was 13,333 boxes and volume of fruit left in the grove was 2,353 boxes. This corresponded to 29 ha of grove harvester per arm. Annual fixed costs and operating costs were $5,750 and $9,723, respectively. An itemization of operating costs is included in Table 5. Overhead expenses were $1,458. The unpicked fruit expense was $11,765 and was the single largest expenditure. Total annual harvest costs were $28,705/arm, resulting in a harvest cost of $2.15/box. The estimate for 1983-84 hand harvest cost was $1.46/box (Hooks, 1986).

TABLE 5. SUMMARY OF NOMINAL ANALYSIS STATE RESULTS.

Boxes harvested		13,333
Boxes left in grove		2,353
Harvested ha		29
Fixed costs		$5,759
Operating costs		$9,723
Energy cost	$560	
Repair and maintenence	$5,600	
Grove conditioning	$2,163	
Labor	$1,400	
Unpicked fruit expense		$11,765
Overhead expense		$1,458
Total Harvest Costs		$28,705
Harvest costs/box		$2.15

Sensitivity Analysis

The sensitivity of harvest cost/box to changes in a given analysis variable was determined with the following:

$$S_x = \frac{\partial PBC}{\partial x}\bigg|_{x_n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots [11]$$

where PBC is the per box harvest cost as calculated with equation [10] and S_x is harvest cost sensitivity to analysis variable x at x_n, the nominal analysis state. Equation [11] defines the slope of the harvest cost vs. analysis variable x curve at x_n.

Harvest cost sensivity was determined for all analysis variables with the following exceptions. Arm purchase price (APP) and support equipment purchase price (SEPP) were combined into a single variable, harvester purchase price (HPP). Repair and maintenance rates for arm and support equipment were combined into a

TABLE 6. SENSITIVITY ANALYSIS RESULTS.

Rank	Analysis variable	Sensitivity (change in harvest cost/box (PBC) due to a 100% increase in analysis variable)
1	Harvester inefficiency (HI)	$1.07
2	Harvester Purchase Price (HPP)	$0.92
3	Pick cycle time (PCT)	$0.77
4	Composite Repair Rate (CRR)	$0.48
5	Operating time (OT)	−$0.43
6	Depreciation life (DL)	−$0.27
7	Grove conditioning rate (GCR)	$0.19
8	Interest rate (IR)	$0.14
9	Labor rate (LR)	$0.12
10	Overhead rate (OHR)	$0.11
11	Harvester power requirements (HPR)	$0.05
12	Unit energy cost (UEC)	$0.05
13	Shelter expense rate (SE)	$0.01
14	Taxes and insurance (TI)	$0.01

composite repair rate (CRR). Harvest cost sensitivity to citrus production variables (FPB, FPH, and OTV) were not considered.

Analysis variables are ranked according to their influence on harvest cost in Table 6. For comparison purposes, sensitivities were normalized and expressed as the change in per box harvest cost (PBC) due to a 100% increase in the estimated value of the analysis variable. Harvest inefficiency (HI) was the most influential analysis variable followed by harvester purchase price (HPP) and pick cycle time (PCT). Of the five most influential analysis variables, three were harvester performance variables (HI, PCT, OT).

Harvest Cost Estimates

Harvest costs were calculated as functions of the two most influential analysis variables (HI and HPP) at three analysis conditions: optimistic estimates for PCT, CRR, and OT, nominal estimates for these variables and conservative estimates. Harvest inefficiency was varied from 0% to 25% and harvester purchase price was varied from $20,000 to $30,000 (per arm basis). Values for PCT, CRR, and OT corresponding to the optimistic, nominal, and conservative analysis states are given in Table 7. Nominal estimates were used for all other analysis variables.

Harvest cost estimates are plotted in Figs. 2 through 4. In Fig. 2 (optimistic estimates), harvest cost estimates ranged from $0.53/box to $2.43/box. Under the optimistic conditions, robotic harvesting was competitive with hand harvesting at harvest inefficiencies up to 15%. In Fig. 3 (nominal estimates) harvest cost estimates ranged from $1.07/box to $3.10/box. Under nominal conditions, robotic harvesting was competitive with hand harvesting only when harvest inefficiency was less than 1 to 7%, depending on harvester purchase price. Results from the conservative state analysis are shown in Fig. 4. Robotic harvest costs ranged from $2.04/box to $4.67/box and were never below current hand harvest cost.

TABLE 7. ANALYSIS CONDITIONS USED FOR ESTIMATING RANGES IN HARVEST COSTS.

Analysis condition	Analysis variable	Value
Optimistic	PCT	1.5 s
	CRR	5%
	OT	3000 h
Nominal	PCT	3 s
	CRR	10%
	OT	2000 h
Conservative	PCT	4.5 s
	CRR	15%
	OT	1000 h

Harvester inefficiency was varied from 0% to 25% for all conditions.

Harvester purchase price was varied from $20,000 to $30,000 (per arm basis) for all conditions.

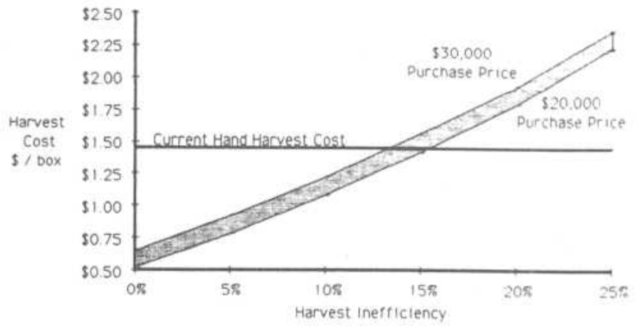

Fig. 2—Robotic harvest cost estimates for optimistic analysis.

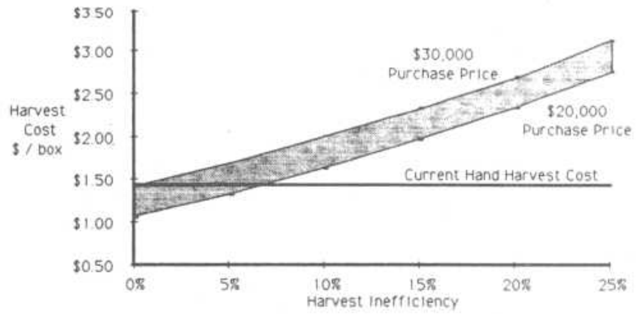

Fig. 3—Robotic harvest cost estimates for nominal analysis.

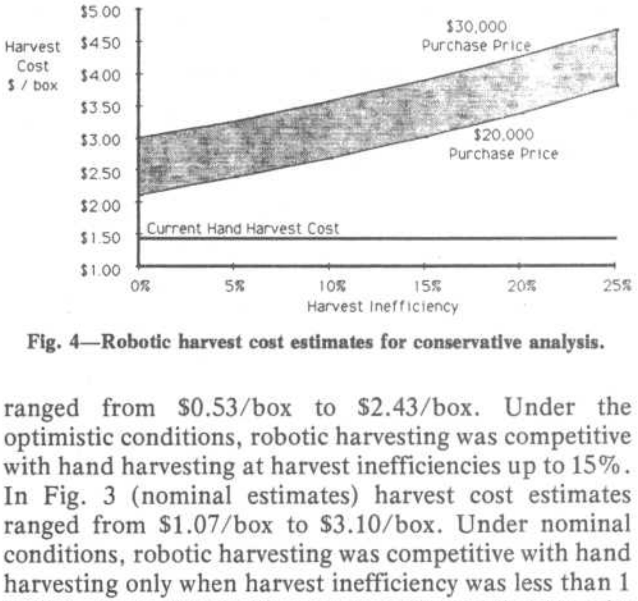

Fig. 4—Robotic harvest cost estimates for conservative analysis.

CONCLUSIONS

The $2.15/box harvest cost estimated at the nominal analysis state was felt to be best representative of robotic harvesting in Florida. This estimate is approximately 50% greater than the average 1983-84 hand harvest cost of $1.46/box published by Hooks (1986). It must be concluded that robotic harvesting, as percieved in this analysis, could not economically compete with hand harvesting at current labor rates. However, if harvest inefficiencies are maintained around the 5% level or if hand harvest costs increase, the economic outlook improves considerably. Therefore, research and development of robotic citrus harvesting technology should continue and should concentrate on those areas which have the greatest potential to reduce harvest cost. These areas are discussed below.

1. Robotic harvest cost was most sensitive to harvest inefficiency. Therefore, a primary design objective should be to minimize harvest inefficiency. A harvest inefficiency of 1 to 7% appears to be required before robotic harvesting reaches the break-even point with manual labor at current hand harvest costs.

2. A per arm harvester purchase price of $20,000 to $30,000 (1986 dollars) appears to be achievable with current technologies. This would put the purchase price of a 10 arm harvesting system between $200,000 and $300,000. Since harvest cost is more sensitive to harvest inefficiency than to harvester purchase price, reducing the price of the harvester by compromising harvester efficiency is probably not justified. Since the sensitivity to harvest inefficiency is only slightly greater than that to purchase price, it does not appear that a significant reduction in harvest cost would result through a more efficient design if it is a more expensive design. Increases in harvester cost are justified if significant reductions in both harvester inefficiency and average pick cycle time result.

3. The expense of robotic harvesters necessitates intensive use for them to be economically practical; 2000 h or more of operation per season may be necessary in many situations. This requires that harvesters be highly reliable in order to minimize maintenance related down time. The intensive use requirement will prohibit owners of small and medium size groves from purchasing their own harvesters. Thus, many harvesters will be operated on a contractual basis by harvesting firms.

4. The condition of the work environment has the potential to significantly affect the three most influential cost factors: harvest inefficiency, harvester purchase price, and pick cycle time and thus, will probably have as much an influence on harvesting costs as the other factors considered in this study. Research is needed to identify the modifications in the work environment that would benefit robotic harvesting and to determine how these modifications could be implemented.

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