

ECONOMIC EVALUATION OF APPLE HARVEST AND IN-FIELD SORTING TECHNOLOGY

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ABSTRACT. *The U.S. apple industry, which generated more than \$2.7 billion in revenue at the farm gate in 2013, is facing critical challenges with decreased availability of labor and increased labor and production costs. To address these challenges, a self-propelled apple harvest and in-field sorting machine is being developed in our laboratory. This article reports on the economic evaluation of this prototype machine by considering machine cost (annual ownership and operating costs), harvest productivity increase (including that due to decreased occupational injuries), and cost savings in postharvest storage and packing resulting from in-field sorting of fresh market quality apples from processing apples for both fresh apple growers and processing apple growers. The economic evaluation was conducted based on the assumptions that the machine increases harvest productivity by 43% to 63% and operates for 360 h during the harvest season. For fresh apple orchards with processing apple incidences of 5% to 15%, the net annual benefits that would accrue from owning one machine range from \$13,500 to \$78,400 when the machine price is between \$100,000 and \$160,000. For processing apple orchards with processing apple incidences of 80% to 90% and the same machine price range, the net annual benefits that would accrue from owning one machine range from \$23,900 to \$81,700. Overall, the benefits gained from in-field sorting outweigh those from the harvest productivity increase, and integration of the harvest-assist and in-field sorting functions is more beneficial to apple growers. This technology will help the U.S. apple industry improve labor productivity and reduce production costs, and thus it looks promising for commercialization.*

Keywords. *Apples, Economic evaluation, Harvest-assist, In-field sorting, Machinery system, Occupational injuries.*

In the U.S., apple is the second most popular fruit (in terms of annual consumption per capita), just behind banana (PBH, 2015). In 2013, the U.S. produced approximately 5 million MT of apples, with total farm-gate revenue of more than \$2.7 billion. Approximately 200 apple cultivars were planted on 160,000 ha by 7,500 apple growers. Thirty-two states grow apples, with the top five being Washington, New York, Michigan, Pennsylvania, and California (USApple, 2015). Table 1 shows summary data of the U.S. apple industry for 2012. Baugher et al. (2009a) reported that increased competition, high cost, poor return, and competing land use threaten the future profitability of the U.S. apple industry, if no technological innovations are adopted.

Currently, apples are hand harvested because of their susceptibility to bruising and the lack of appropriate technologies for mechanical harvesting. Workers use buckets and ladders to pick apples from trees, and harvested fruit are then

placed in storage bins, each of which can hold about 400 kg of apples. A typical bucket weighs approximately 19 kg when full (Freivalds et al., 2006; Zhang et al., 2016b). Apple harvest mainly relies on migrant and seasonal agricultural employees, and it accounts for 16% of the total apple production cost (Gallardo et al., 2010; Gallardo and Galinato, 2012). The availability and cost of agricultural employees have become a major concern for the U.S. apple industry (Morgan, 2002; Hansen, 2004). Since the 1980s, growers have found it increasingly difficult to obtain skilled labor for apple harvest (Domigna et al., 1988). A key reason for the shrinking labor pool is the strength and endurance required of workers (Zhang et al., 2014; Zhang and Heinemann, 2017). Hand harvest is physically demanding and makes workers prone to occupational injuries, such as strains and sprains (Isaacs and Bean, 1995). The frequent occurrences of occupational injuries are attributed to awkward harvest activities, such as ladder climbing with a full bucket, bending forward to release apples into the bin, and persistently carrying partially filled or full buckets (Sakakibara et al., 1995; Bernard, 1997; Earle-Richardson et al., 2005; Proto and Zimbalatti, 2010). Furthermore, ladder falls are the most common accidents and can result in serious injuries, such as strains, sprains, fractures, or even deaths (McCurdy et al., 2003; Salazar et al., 2005; Fathallah, 2010). To alleviate the tough working conditions and reduce occupational injuries, Earle-Richardson et al. (2004, 2005, 2006a) developed an ergonomic hip belt for apple workers to redistribute the bucket weight from the trunk to the hips. Earle-Richardson et al. (2006a) and Freivalds et al. (2006) demonstrated that

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Table 1. Summary data of U.S. apple industry for 2012.

State	No. of Farms ^[a]	Production Area (ha) ^[b]	Average Farm Size (ha) ^[b]	Average Yield (MT ha ⁻¹) ^[b]	Total Production (× 10 ⁶ MT) ^[b]	Fresh Apple Percentage (%) ^[b]	Processing Apple Percentage (%) ^[b]
Washington	2,521	59,896	23.8	44.7	2.7	87.0	13.0
New York	1,066	16,188	15.2	39.6	0.6	53.4	46.6
Michigan	1,299	14,772	11.4	38.7	0.6	50.0	50.0
Pennsylvania	1,239	8,094	6.5	26.3	0.2	30.0	70.0
California	1,984	6,151	3.1	20.0	0.1	45.0	55.0
U.S. total	18,815	130,665	17.2	36.2	4.7	67.0	33.0

^[a] USDA (2015a).

^[b] USDA (2012).

the hip belt significantly reduced muscle activities, potentially lowering, but not eliminating, occupational injuries. However, commercial adoption of these strain-alleviating devices has been slow (Chapman et al., 2004, 2008) due to cost, performance, and harvest productivity concerns.

In recent years, an increasing number of apple orchards in the U.S. have been transformed into high-density structured orchard systems, which not only enhance fruit yield and quality but also improve orchard management efficiency. Accompanied with this orchard system evolution is the increasing use of self-propelled harvest platforms by growers (Baugher et al., 2009b; Fathallah, 2010; Sazo et al., 2010; Schupp et al., 2011; Robinson and Sazo, 2013; Sazo and Robinson, 2013; Zhang et al., 2016b, 2017a). These harvest platforms increase harvest productivity, helping reduce the required amount of harvest labor and thus harvest cost (Sazo et al., 2010; Luo et al., 2012; Zhang, 2015; Zhang et al., 2014, 2016a, 2017b). Moreover, they can also significantly reduce occupational injuries by eliminating or reducing such awkward activities as stretching to reach high apples and moving a ladder in the orchard (Earle-Richardson et al., 2005).

Postharvest handling is a major cost in apple production. Wunderlich et al. (2007) reported that the cost for sorting, packing, and selling ‘Fuji’ apples accounted for 37.4% of the total production cost. Currently, all harvested apples of mixed quality grades are hauled to a shed for storage. These apples are kept in refrigerated storage or controlled atmosphere (CA) storage until being taken to a packing facility for sorting and grading. While fresh and processing apples incur the same costs in postharvest handling (i.e., storage, grading, sorting, and packaging) (Mizushima and Lu, 2011), they are usually sold at different prices, e.g., \$0.8 kg⁻¹ for fresh apples (USDA, 2015c) versus \$0.2 kg⁻¹ for processing apples (Lehnert, 2015). Because of the low price of processing apples and the high costs for postharvest storage and packing, growers may not break even if a high percentage of processing apples is present in the lot. For instance, it has been reported that the price of juice or processing apples received by apple growers was lower than that charged by the warehouse for postharvest handling (Schotzko and Granatstein, 2005; Lehnert, 2013). When this situation happens, growers would rather choose to dump juice apples in the orchard. Moreover, mixing inferior or defective fruit with good fruit can cause potential devastating economic loss to growers because defective fruit are susceptible to disease and pest invasion during postharvest storage, which can spread to good fruit in the same bins. Hence, in-field sorting of processing

and fresh apples has potential to help growers achieve significant savings in postharvest handling. However, automatic in-field sorting technology currently is not available, and manual sorting in the orchard is not likely to be cost-effective. If workers need to perform manual in-field sorting, their harvest productivity would be greatly reduced, which would in turn increase harvest cost for growers. Growers will not accept decreased harvest productivity because of the limited labor pool and short harvest time window. After performing cost-benefit analyses, Mizushima and Lu (2011) concluded that automated in-field apple sorting technology could bring much benefit to apple growers.

Several years ago, our laboratory initiated a research project on the development of computer vision-based technology that can be readily incorporated into existing or new commercial harvest platforms. A low-cost computer vision-based apple presorting system was developed for sorting and grading apples into two quality grades (i.e., fresh and processing). The patent-pending sorting system has several innovative features for fruit transporting, singulating, and sorting (Lu et al., 2016). In addition, new bin fillers were developed for working with the sorting system to place graded apples into individual bins. In collaboration with a commercial equipment manufacturer, we designed and constructed a first version of the self-propelled apple harvest and automated in-field sorting machine in 2016. The new machine combines the harvest-assist and in-field sorting functions into one system to achieve greater economic benefits for apple growers. Several innovative design features are incorporated into this new machine prototype for enhancing harvest productivity and reducing downtimes or disruptions for the harvest crew during the handling of empty and full bins (a further description of the machine is given in the Materials and Procedures section). Initial tests of the new apple harvest and sorting machine were conducted in a commercial orchard in Michigan during the 2016 harvest season.

The current study was focused on economic evaluation of the new harvest and in-field sorting machine for the U.S. apple industry. Considered in the economic evaluation were the increase in harvest productivity, reduction in occupational injuries, postharvest handling cost savings for fresh apple growers, and benefits that would be gained for processing apple growers due to adoption of in-field sorting technology. By factoring in the occupational injuries and harvest productivity improvement, this study has extended and updated the earlier study by Mizushima and Lu (2011), which only considered potential cost savings in postharvest storage and packing.

METHODS AND PROCEDURES

BRIEF DESCRIPTION OF APPLE HARVEST AND IN-FIELD SORTING MACHINE

The economic evaluation in this study was conducted for the self-propelled apple harvest and in-field sorting prototype that is being developed in our lab (figs. 1 and 2). This prototype was designed to accommodate a harvest crew of six workers, and it can sort apples into two quality grades (i.e., fresh and processing) at a throughput of up to 9 fruit s^{-1} . The prototype is equipped with three pairs of mechanical harvest conveyors that allow workers, standing either on the ground

or on elevated harvest platforms, to pick fruit from the trees at different heights and then conveniently place the harvested fruit on the conveyors. Fruit on the conveyors are then transported to a specially designed fruit singulating and rotating device, which separates and rotates the fruit as they are moving forward. After the fruit enter the computer vision chamber, a color digital camera automatically acquires multiple images of the fruit at a rate of 15 frames s^{-1} . Depending on the conveyor speed, the camera captures 15 to 20 images of each fruit under artificial illumination (i.e., LED lighting) to ensure that the entire surface of the fruit is imaged at least once. An in-house developed computer program automatically tracks each

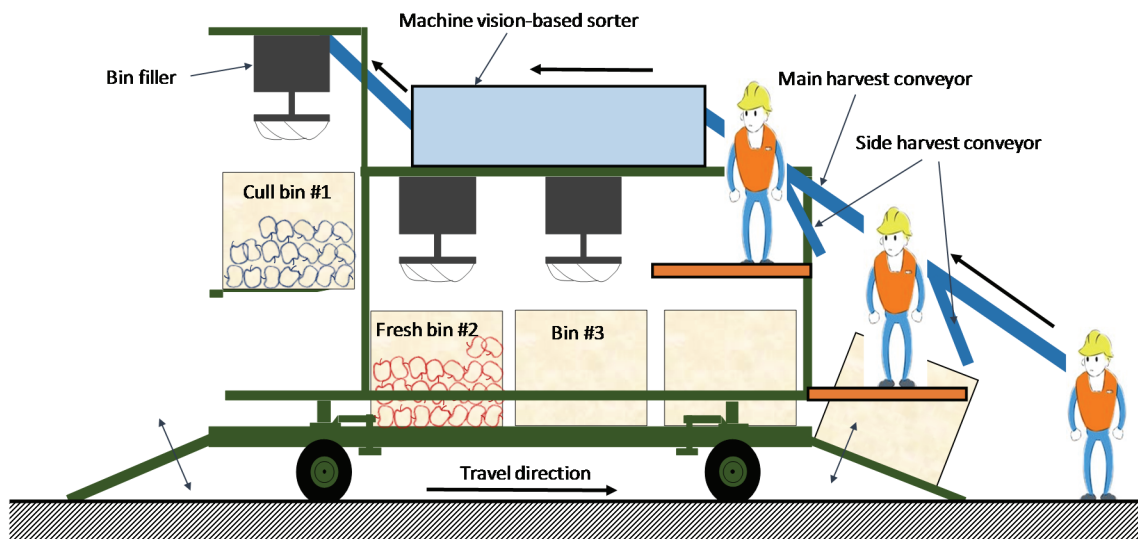


Figure 1. Schematic of newly developed harvest and in-field sorting machine (Pothula et al., 2016).



Figure 2. Apple harvest and in-field sorting prototype machine tested in a commercial orchard in Michigan during the 2016 harvest season.

fruit and performs image processing based on fruit size or shape and color to determine the quality grade. Growers can use the default settings in the program for quality grading, or they can also set their own grading standards through simple manual training of the computer program for each variety of apple. After the quality grade of the fruit is determined, the computer sends signals to a rotary sorter, which automatically directs the graded apples to specific bins. Bin filling is an important operation in which the graded apples received from the sorter are distributed into the bins evenly and gently, with no or minimal bruising damage to the fruit. This is accomplished by using three newly designed, cost-effective bin fillers, which are fully automated through onboard microchip processors to control the up and down movement of the bin fillers to minimize bruising damage to the fruit. Another important feature of the prototype is automatic handling of empty and full bins with no or minimal disruption to the harvest crew.

YEARLY MACHINE COST ESTIMATION

In this study, the machine was assumed to operate 10 h per day for 36 days per season. Thus, it operates for 360 h yearly. The costs of the self-propelled apple harvest and in-field sorting prototype can be divided into two categories: annual ownership cost and operating cost (ASABE, 2011a, 2011b; Edwards et al., 2005; Edwards, 2015). Annual ownership costs are incurred even without using the machine, while operating costs are directly related to the amount of machine use.

Annual Ownership Cost

The ownership (fixed) cost begins with the purchase of the machine and continues for as long as the grower owns the machine until it is sold or no longer operable (Kay et al., 2004). The annual ownership cost was calculated according to the following equations (ASABE, 2011b):

$$C_A = P_M \times C_0 \quad (1)$$

$$C_0 = \frac{1 - S_V}{L} + \frac{1 + S_V}{2} \times i + K_2 \quad (2)$$

where

- C_A = annual ownership cost
- P_M = new machine purchase price
- C_0 = ownership cost coefficient (decimal)
- S_V = machine salvage value factor at the end of the machine life, i.e., year L
- L = machine life (years)
- i = annual interest rate
- K_2 = ownership cost factor, including taxes, housing, and insurance.

The annual ownership cost consists of depreciation, interest (opportunity cost), taxes, insurance, and housing. The housing cost means providing shelter, tools, and maintenance equipment for machinery, so as to result in fewer repairs in the field and less deterioration of mechanical parts and appearance from weathering (Edwards, 2015). Based on Edwards (2015) and Mizushima and Lu (2011), the machine life, remaining machine salvage value factor, and annual interest rate were selected to be 10 years, 10%, and 7%, respectively. Taxes, insurance, and housing were 1%, 0.75%, and 0.25%,

respectively, for a total of 2%. By substituting these numbers into equation 2, the ownership cost coefficient (C_0) was calculated to be 0.1485:

$$C_0 = \frac{1 - 0.1}{10} + \frac{1 + 0.1}{2} \times 0.07 + 0.02 = 0.1485 \quad (3)$$

Operating Cost

Expenditures on repair and maintenance due to part failure, wear, accident, and natural deterioration are necessary to keep the machine operable. The operating cost (variable cost) is highly variable from one geographic region to another because of terrain, climate, and other conditions. Even in the same local area, operating cost varies from one orchard to another, mainly due to different management practices and operator skills. The operating cost was estimated based on ASABE Standard EP496.3 (ASABE, 2011b), which is closely related to machine use hours, repair and maintenance cost, fuel cost, and lubrication cost.

The annual repair and maintenance cost is related to the repair and maintenance factor, accumulated use hours, and new machine purchase price, and it was calculated using the following equations:

$$C_{rm} = P_M \times C_1 \quad (4)$$

$$C_1 = RFI \times \left(\frac{h}{1000} \right)^{RF2} \quad (5)$$

where

- C_{rm} = accumulated annual repair and maintenance cost
- C_1 = accumulated annual repair and maintenance cost coefficient (decimal)
- $RF1$ = repair and maintenance factor 1
- $RF2$ = repair and maintenance factor 2
- h = accumulated annual use of machine (h).

In this study, the machine life was assumed to be 10 years, and thus the total working life of the machine was estimated to be 3,600 h (10 years \times 360 h per year). Based on the 3,600 h working life, $RF1$ and $RF2$ were determined to be 0.11 and 1.8, respectively (ASABE, 2011a). Hence, the accumulated annual repair and maintenance cost coefficient (C_1) was equal to 0.017, according to the following equation:

$$C_1 = 0.11 \times \left(\frac{360}{1000} \right)^{1.8} = 0.017 \quad (6)$$

The self-propelled apple harvest and in-field sorting machine is powered by a 28 hp gasoline engine, and the fuel consumption cost was estimated based on ASABE Standard EP496.3 (ASABE, 2011b) using the following equation:

$$Q_{avg} = 0.13 \times P_{pto} \quad (7)$$

where

- Q_{avg} = average gasoline consumption cost (\$ h⁻¹)
- P_{pto} = maximum power take-off (PTO) (hp).

The gasoline price was estimated to be \$0.58 L⁻¹ (\$2.21 gal⁻¹) (EIA, 2016), and this price was used to calculate the annual fuel consumption cost. In this study, the maximum PTO was assumed to be equal to the engine power (28 hp).

Thus, the estimated average gasoline consumption cost (Q_{avg}) was $\$3.64 \text{ h}^{-1}$, which is conservative because higher fuel cost was assumed.

Edwards (2015) reported that the lubrication cost was about 15% of the fuel cost. Therefore, based on the fuel cost equation (eq. 7), the lubrication cost (L_{avg}) is given by the following equation:

$$L_{avg} = 0.15 \times Q_{avg} = 0.0195 \times P_{pto} \quad (8)$$

which was calculated to be $\$0.546 \text{ h}^{-1}$.

Annual Machine Cost

The total annual machine cost includes the annual ownership cost and the operating cost, and it is closely related to the machine price. Jones (2015) reported on two commercial apple harvest platforms, i.e., the Pluk-O-Trak apple harvester (Munckhof, Horst, The Netherlands) at a price of $\$78,400$ and the DBR vacuum apple harvester (DBR Conveyor Concepts, Conklin, Mich.) at $\$126,500$. Compared to those two harvesters, our machine has more innovative functions (i.e., automated in-field sorting and bin handling). However, the actual price of the machine for commercial use is yet to be determined. Hence, we chose a price range of $\$60,000$ to $\$160,000$ for our cost-benefit analysis of the machine.

YEARLY COST SAVINGS ESTIMATION FOR HARVEST LABOR

Harvest Productivity Increase Due to Decreased Occupational Injuries

Agricultural employment is one of the nation's most hazardous careers. Leigh et al. (2001) reported that the cost of agricultural occupational injuries was estimated at $\$4.6$ billion in 1992. Agricultural employees are exposed to musculoskeletal disorders, ladder falls, dermatitis, and hearing loss due to noise (Coye, 1985; Purschwitz and Field, 1990; Moses, 1989; Litchfield, 1999). Earle-Richardson et al. (2008) reported that the occupational injury morbidity was 4% for orchard workers. The leading injuries were back, neck, and shoulder strains/sprains, which constituted 37% of all occupational problems. The second most serious problem was ladder falls, which accounted for 12% of all occupational problems (Earle-Richardson et al., 2006b). Husting et al. (1997) and McCurdy et al. (2003) found that strains/sprains were the most common type of injury, accounting for 31% of all injuries. Demers and Rosenstock (1991) reported that strains/sprains constituted 33% of agricultural injuries. Brower et al. (2009) showed that musculoskeletal strains/sprains had a morbidity of 39%. In this research, the strains/sprains morbidity was estimated at 35% based on the averaged morbidity of those previous studies. By standing on the harvest platform to pick apples at a comfortable posture, workers do not stretch/bend their bodies, move heavy ladders in the orchard, or carry a heavy harvest bucket. Hence, it was reasonable to assume that strains/sprains would be eliminated. Because no data on the effects of strains/sprains on apple harvest productivity are available in the literature, this research used a self-reported reduction in productivity due to strains/sprains of 14%, as reported by computer users, as a reference (Taylor et al., 2008). In view

of the fact that the strength demand for apple harvest activities is much greater than that for computer use, it was reasonable to estimate the productivity reduction at 42% for apple harvesting, which is three times that for computer users. As a result, the total productivity reduction caused by sprains and strains was calculated to be 0.59% based on the following equation:

$$PR_{ss} = M_{oi} \times M_{ss} \times P_{r_{ss}} \quad (9)$$

where

PR_{ss} = productivity reduction caused by strains/sprains

M_{oi} = morbidity of occupational injuries (4%)

M_{ss} = morbidity of strains/sprains (35%)

$P_{r_{ss}}$ = productivity reduction caused by strains/sprains (42%).

Ladder falls are the second most serious cause of injury for agricultural employees and can cause such injuries as fractures, strains/sprains, and open wounds (Smith et al., 2006; Stevens et al., 2006; Lombardi et al., 2011). Cohen and Lin (1991a) reported that the top three scenarios for ladder falls were overreaching, slips on rungs, and missteps on rungs. Hofmann et al. (2006) conducted research on agricultural occupational injuries in Washington State orchards and identified the top three ladder-related claims among orchard workers to be strains/sprains (38%), contusions (26%), and fractures/dislocations (12%). Ladder fall injuries can result in being absent from work for several months or longer when fractures/dislocations occur, and even strains/sprains and contusions caused by ladder falls can cause agricultural employees to be unemployed for more than a month (Cohen and Lin, 1991b; Axelsson and Carter, 1995). Standing on the harvest platform to pick apples, employees do not need to use a ladder, thus eliminating the risk of ladder-related injuries. If a ladder fall happens, it is reasonable to assume that the injured worker loses the ability to work for the entire harvest season, or for the rest of the season, and the productivity reduction is 100% (assuming 36 days for the harvest season). Contusions were assumed to have the same work productivity reduction as sprains/strains. As a result, the total productivity reduction caused by ladder falls was calculated to be 0.1866% based on the following equation:

$$PR_{lf} = M_{oi} \times M_{lf} \times (M_{lss} \times PR_{lss} + M_{lrc} \times PR_{lrc} + M_{lfd} \times PR_{lfd}) \quad (10)$$

where

PR_{lf} = productivity reduction caused by ladder falls

M_{lf} = morbidity of ladder falls in the occupational injuries (12%)

M_{lss} = morbidity of strains/sprains caused by ladder falls (38%)

PR_{lss} = productivity reduction caused by strains/sprains from ladder falls (42%)

M_{lrc} = morbidity of contusions caused by ladder falls (26%)

PR_{lrc} = productivity reduction caused by contusions from ladder falls (42%)

M_{lfd} = morbidity of fracture/dislocation caused by ladder falls (12%)

PR_{lfa} = productivity reduction caused by fracture/dislocation from ladder falls (100%).

Thus, the total decrease in apple harvest productivity due to occupational injuries for the conventional apple harvest method is equal to the sum of the productivity reductions caused by sprains/strains and ladder falls. By adopting the harvest-assist platform, agricultural employees could increase harvest productivity by 0.90% (eq. 11):

$$HP_i = \frac{1}{(1 - PR_{ss} - PR_{lf})} - 1 \quad (11)$$

where HP_i is the harvest productivity increase. Because of the limited data available on other more serious results caused by ladder falls (e.g., deaths), which were not included in the above calculations, this research assumed that harvest productivity would increase by 3% (three times the calculated known occupational injuries) by replacing ladder use with the harvest platform.

Harvest Productivity Increase Due to Harvest-Assist Platforms

Our apple harvest and in-field sorting machine, when finally ready for commercial use, will have the following important features for harvest productivity improvement: (1) automatic bin handling with no or minimal disruption of fruit picking, (2) fingered conveyor belts instead of buckets for handling harvested apples, and (3) automatic steering. Hence, there will be no need for a dedicated worker to drive the machine or handle the filled and empty bins. As the machine travels in the orchard, it picks up empty bins in front and moves them into appropriate positions via computer control, while unloading the full bins behind (figs. 1 and 2). When the processing apple or cull bin (bin #1 in fig. 1) is full, bin #3 will be used for holding culls until the fresh bin (bin #2) is full. When the fresh bin (bin #2) is full and unloaded, the cull bin (bin #3) will then be moved to the position of bin #1. By using these design features coupled with automatic computer control for handling the bins, our machine will cause minimal downtimes or disruptions for workers during bin handling.

To estimate the harvest productivity improvement by our machine compared to manual harvest (i.e., buckets and ladders), it is necessary to look into existing commercial harvest platforms. Several recent studies (Baugher et al., 2009a; Robinson et al., 2013; Robinson and Sazo, 2013) reported that the harvest productivity improvements with different commercial harvest platforms ranged from 15% to 60%. The Huron harvest platform, shown in figure 3, could improve harvest productivity by 40% (Robinson and Sazo, 2013). It can handle empty and filled bins continuously, with minimal disruption to the workers. However, workers need to carry buckets to temporarily hold harvested apples and then manually place apples in the bins, which would reduce harvest productivity and increase the physical strength demands for the workers, compared to the harvest conveyor design used in our machine.

In contrast, the DBR vacuum harvest-assist platform (fig. 4) uses flexible tubes that operate with vacuum pressure for transporting harvested apples to the bins. Jones (2015)



Figure 3. Huron harvest-assist platform (Huron, 2016).



Figure 4. DBR vacuum harvest-assist platform (PBW, 2016).

reported that the DBR platform, with four workers picking fruit and one handling the bins, could achieve 24 bushels of apples per man-hour (with all five workers considered). By excluding the worker not involved in apple picking, each worker could pick 30 bushels of apples in an hour. Gillman (2016) reported that with the conventional harvest approach (using ladders and buckets), a professional apple worker could pick 20 bushels per man-hour. Hence, the DBR platform could increase the overall harvest productivity (including the pickers and bin handler) by 20% (i.e., 24 bushels per man-hour with the DBR platform versus 20 bushels per man-hour with the conventional approach), and the harvest productivity excluding the bin-handling worker could be improved by 50% (i.e., 30 bushels per man-hour). For both the DBR platform and our machine, workers do not need to carry a bucket for holding fruit temporarily. The workers on our machine place apples onto the conveyor belts, while those on the DBR platform place fruit into the vacuum tubes. Hence, the harvest productivity for the two machines should be about the same. However, the automatic bin handling feature of our machine, which eliminates the need for a dedi-

Table 2. Labor cost savings for different harvest productivity increases.

Harvest Productivity Increase	Total Labor Cost Savings		
	(\$ ha ⁻¹)	(\$ MT ⁻¹) ^[a]	(\$ bin ⁻¹)
43%	930	20	8
53%	1070	23	9
63%	1200	26	10

^[a] Calculated by assuming apple production at 124 bin ha⁻¹ (50 bin acre⁻¹) with each bin containing 0.378 MT of apples.

cated bin-handling worker, can further increase the harvest productivity by decreasing downtimes. Jones (2015) reported that 9 min were needed to fill a bin with the DBR platform, plus 1 min for bin swap, during which time the workers suspended their picking activities. Thus, the continuous automatic bin handling of our machine can increase the harvest productivity by an additional 10%.

In summary, by comparing our machine with the Huron and DBR harvest platforms, we have reached a reasonable but conservative estimate that our machine can achieve harvest productivity improvements in the range of 40% to 60%.

Harvest Labor Cost

Gallardo et al. (2010) and Gallardo and Galinato (2012) reported a harvest labor cost of \$66 MT⁻¹ for ‘Gala’ and ‘Delicious’ apples in Washington State. Because Washington is the major apple-producing state in the U.S. and thus would be a major state for future use of our machine, it was reasonable to use the harvest labor cost of \$66 MT⁻¹ in this study.

Total Labor Cost Saving Estimation

Workers are usually paid on a piece-rate basis or by their working hours (McCurdy et al., 2003). In most areas, even though workers are paid based on how much they have harvested, they are also guaranteed at least a minimum hourly wage (Fox, 2011). In our calculation of the machine’s economic benefits, workers were assumed to be paid hourly. By adopting the harvest and in-field sorting machine, apple growers would benefit by reducing harvest cost because workers can harvest more apples in an hour. In our analysis, we have shown that the productivity increase due to decreased occupational injuries was estimated to be 3%, and the productivity increase due to the harvest platform ranged from 40% to 60%. Hence, in further analysis, we looked at three total harvest productivity increases of 43%, 53%, and 63% (i.e., 40%, 50%, and 60% increases in harvest productivity by adopting the harvest-assist platform, plus a 3% increase due to the decrease in occupational injuries). Because the harvest labor cost for conventional harvesting with ladders was estimated to be \$3,089 ha⁻¹ for a yield of 124 bins ha⁻¹ (\$66 MT⁻¹), the harvest labor cost would decrease to \$2,160, \$2,019, and \$1,895 ha⁻¹ for harvest productivity increases of 43%, 53%, and 63%, respectively, by adopting the harvest platform. Total labor cost savings for different harvest productivity increases are shown in table 2.

MACHINE CAPACITY

In this study, the harvest rate refers to the number of apples a crew of six workers can pick in 1 s, which cannot exceed the sorting rate of the machine vision system. For fresh apple growers, the sort-out rate is the number of sorted-out processing apples divided by the total number of processing apples. For processing apple growers, the sort-out rate is the

Table 3. Harvest rate and machine capacity for different harvest productivity increases (calculated for a harvest crew of six workers).

	Harvest Productivity Increase		
	43%	53%	63%
Harvest rate (apples s ⁻¹)	6.00	6.42	6.84
Machine capacity (MT season ⁻¹)	1177.2	1259.5	1341.8

number of sorted-out fresh apples divided by the total number of fresh apples.

Gillman (2016) reported that professional apple workers could pick 20 bushels (1 bin) per man-hour with the conventional harvest method (ladders and buckets). Conservatively assuming that seven apples weigh about 1 kg (Kerchers, 2013), a typical professional worker can pick apples at a harvest rate of 0.7 apples s⁻¹. Table 3 shows the machine capacities for the three harvest productivity increases for a harvest crew of six workers. The sorting system is designed to work at a throughput of up to 9 apples s⁻¹, which is equal to a capacity of 1,764 MT per season. Hence, the machine would more than fulfill the harvest capacity requirement, even at the estimated maximum harvest productivity increase of 63%. The average orchard production (i.e., multiplying average orchard size by average yield) was 1,064 MT, 602 MT, 441 MT, 171 MT, and 62 MT, for Washington, New York, Michigan, Pennsylvania, and California, respectively (table 1). Hence, this machine may not be cost-effective for smaller orchards, such as those in Pennsylvania and California. These orchards would need to share a machine and coordinate their harvest schedules in order to run the machine at the full capacity and gain the full benefits of adopting the technology. In this study, the machine was assumed to run at full capacity.

YEARLY COST SAVINGS FOR POSTHARVEST HANDLING OF PROCESSING APPLES

Mizushima and Lu (2011) gave cost estimations for cooling, grading, and storing of \$160 MT⁻¹ and \$130 MT⁻¹ for mixed apples and fresh apples, respectively. Based on the information available in the literature (Caprile et al., 2001; Wunderlich et al., 2007) and personal communication with two commercial packinghouses (Riveridge Packing LLC and Elite Apple Co. LLC) in Sparta, Michigan, the costs of different postharvest handling services used in this study are shown in table 4. Processing apples are assumed to be kept in cold storage and need not go through sorting/grading/packaging, while fresh apples and mixed quality apples (fresh apples mixed with processing apples) would be stored in CA storage and go through sorting/grading/packaging.

The in-field sorting system was assumed to achieve a 90% sort-out rate for processing apples, which means that 10% of processing apples would remain with fresh apples. The mixed quality apples would be charged \$370 MT⁻¹ for

Table 4. Costs for storage and sorting/grading/packaging of apples.^[a]

Packinghouse Service ^[b]	Cost	
	(\$ MT ⁻¹)	(\$ bin ⁻¹)
CA storage	80	30
Cold storage	30	12
Sorting/grading/packaging	290	110

^[a] Sources: Mizushima and Lu (2011), Riveridge Packing LLC (personal communication, 23 Nov. 2016), and Elite Apple Co. LLC (personal communication, 23 Nov. 2016).

^[b] CA is controlled atmosphere storage for long-term storage. Cold storage is refrigerated storage for short-term storage.

CA storage and sorting/grading/packaging, while the processing apples would be charged \$30 MT⁻¹ (for cold storage only). For example, when 10 MT of mixed apples with 40% processing apples are transported to the packinghouse without prior in-field sorting, the packinghouse cost would be \$3,700 (10 MT × \$370 MT⁻¹). After adoption of in-field sorting (40% processing apples and 90% sort-out rate), 3.6 MT of processing apples would be sorted out in the orchard, and the postharvest handling fee for these sorted-out processing apples would be \$108 (3.6 MT × \$30 MT⁻¹). The remaining 6.4 MT apples of mixed quality would be charged \$2,368 (6.4 MT × \$370 MT⁻¹). By using the in-field sorting technology, the total postharvest cost for the 10 MT of apples would be \$2,476 (\$108 + \$2,368), resulting in a cost saving of \$1,224 (\$3,700 – \$2,476).

Table 1 shows that the average apple yield ranges from 20 to 45 MT ha⁻¹ among the five major apple-producing states, and the percentage of processing apples ranges from 13% to 70%. However, if the percentage of processing apples is greater than 43%, it is reasonable to assume that apple growers will not grade/sort/package these apples because of the high postharvest packing costs and low price for processing apples. This is because growers determine how to handle their apples based on the potential benefit they can obtain. The benefit consists of the higher price for sorted-out fresh apples versus sorted-out processing apples, e.g., \$810 MT⁻¹ vs. \$210 MT⁻¹. For example, if a grower had 100 MT of apples, postharvest handling as fresh apples would cost \$37,000 (100 MT × \$370 MT⁻¹) (table 4), and the total benefit would be \$81,000 (100 MT × \$810 MT⁻¹). If the 100 MT apples were handled as processing apples, the postharvest cost would be \$3,000 (100 MT × \$30 MT⁻¹) (table 4), and the total benefit would be \$21,000 (100 MT × \$210 MT⁻¹). By handling the apples as fresh apples, the grower would incur a higher cost but would also receive a greater benefit. The following equations show the benefits of handling 100 MT apples (with a processing apple percentage of *A*) as fresh apples (*B*) and as processing apples (*C*):

$$B = 100 \times A \times 210 + 100 \times (1 - A) \times 810 - 100 \times 370$$

$$C = 100 \times 210 - 100 \times 30$$

When *B* = *C*, the value of *A* was calculated to be 43%. Thus, when the percentage of processing apples is greater than 43%, the grower would not have an incentive to sort/grade/package the apples for the fresh market.

For fresh apples growers, the postharvest cost savings resulting from in-field sorting of processing apples for various yields and processing apple percentages are shown in table 5. More savings would be achieved when a high yield

Table 5. Postharvest cost savings by adopting in-field sorting of processing apples for different yields and percentages of processing apples, assuming 90% sort-out rate for processing apples (values are U.S. dollars per hectare).^[a]

Yield (MT ha ⁻¹)	Percentage of Processing Apples			
	10%	20%	30%	40%
20	612	1,224	1,836	2,448
25	765	1,530	2,295	3,060
30	918	1,836	2,754	3,672
35	1,071	2,142	3,213	4,284
40	1,224	2,448	3,672	4,896
45	1,377	2,754	4,131	5,508

^[a] Cost savings calculations were based on the data in table 4.

and a high percentage of processing apples occur simultaneously because more processing apples would be sorted out.

RESULTS AND DISCUSSION

If an apple grower purchases the apple harvest and in-field sorting machine, the total cost includes the fixed cost (machine ownership cost) and variable cost (repair/maintenance, fuel, and lubrication). For a fresh apple grower whose primary goal is to sell the highest possible percentage of fresh apples, the benefits of adopting the machine include savings on labor cost (due to increased harvest productivity) and savings from in-field sorting (due to decreased packinghouse cost for processing apples). However, if the orchard's production is primarily processing apples, the grower could receive additional revenue by selling sorted-out fresh apples that would otherwise be used for processing. The harvest and sorting machine would have potential for commercialization only when the benefits outweigh the machine cost.

ANNUAL MACHINE COST

The annual machine cost increases with an increase in the machine price (table 6); it varies from \$11,497 to \$28,096 for a machine price ranging from \$60,000 to \$160,000. Both the annual ownership cost and repair/maintenance costs increase linearly with the machine price, while the fuel and lubrication costs do not change because they are only related to the annual machine operating hours. Table 6 shows that the ownership cost is the main cost component and accounts for as much as 85% of the total cost when the machine price is \$160,000.

BENEFITS FOR FRESH APPLE GROWERS

In general, orchards that produce fresh market apples are more intensively managed than those for processing apples, and they tend to produce a lower percentage of processing apples (Mizushima and Lu, 2011). For instance, orchards in Washington State only produce 13% processing apples (table 1). Hence, in calculating the benefits for fresh apple growers, we only considered processing apple rates up to 20%, with a processing apple sort-out rate of 90%. The annual net economic benefits (total benefits subtracted by total costs) for fresh apple growers who adopt the harvest and sorting machine are summarized in figures 5, 6, and 7 for

Table 6. Annual machine costs for different machine prices (all values are U.S. dollars).

Machine Price	Costs				Annual Machine ^[a]
	Ownership	Repair and Maintenance	Fuel	Lubrication	
60,000	8,910	1,049	1,337	201	11,497
70,000	10,395	1,224	1,337	201	13,157
80,000	11,880	1,399	1,337	201	14,817
90,000	13,365	1,574	1,337	201	16,477
100,000	14,850	1,749	1,337	201	18,137
110,000	16,335	1,924	1,337	201	19,796
120,000	17,820	2,099	1,337	201	21,456
130,000	19,305	2,273	1,337	201	23,116
140,000	20,790	2,448	1,337	201	24,776
150,000	22,275	2,623	1,337	201	26,436
160,000	23,760	2,798	1,337	201	28,096

^[a] Annual machine cost is the sum of ownership cost, repair and maintenance cost, fuel cost, and lubrication cost.

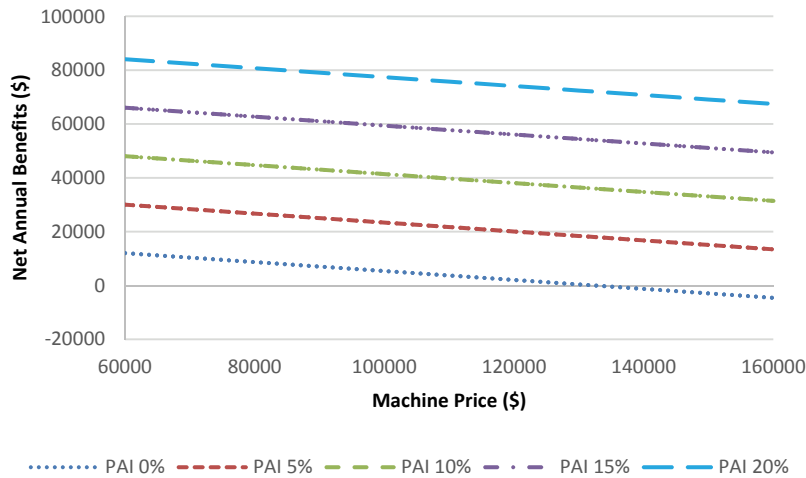


Figure 5. Net annual benefits for fresh apple growers from the apple harvest and sorting machine with 43% harvest productivity increase at different machine prices and processing apple incidences (PAIs). The machine was assumed to run at full capacity of 360 h per season.

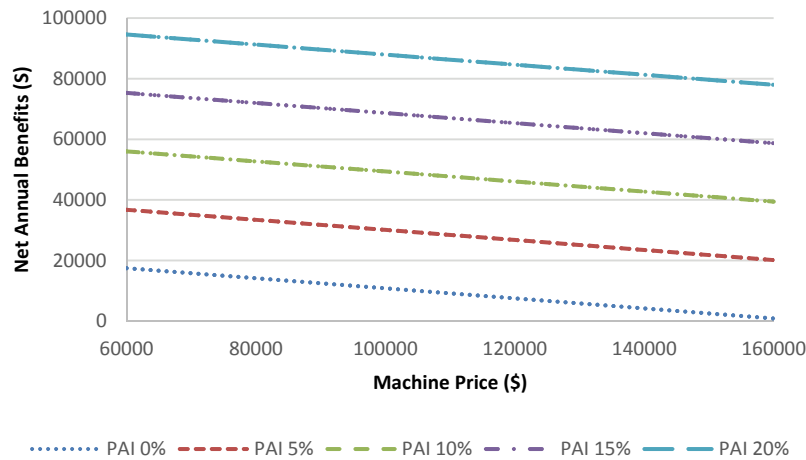


Figure 6. Net annual benefits for fresh apple growers from the apple harvest and sorting machine with 53% harvest productivity increase at different machine prices and processing apple incidences (PAIs). The machine was assumed to run at full capacity of 360 h per season.

harvest productivity increases of 43%, 53%, and 63%, respectively. Processing apple incidence (PAI) refers to the percentage of harvested apples that are graded as processing apples by the machine vision system based on the surface color and size of the fruit, as well as the presence of surface defects. Different growers or packinghouses may set different criteria for processing apples. With the default settings of the current sorting system, an apple is graded as processing when the measured off-color area exceeds 30% of the entire fruit surface or when the size of the fruit (the mean diameter measured at the equator) is less than 64 mm (2.5 in.). For a given harvest productivity increase, the higher the PAI is, the more benefits the machine can bring because the machine can sort out more processing apples, thus reducing the packinghouse costs. When the PAI is 0%, the machine operates as if it were purely a harvest-assist platform, with no in-field sorting function. Figures 5 through 7 show that the in-field sorting function brings much more positive benefits to fresh apple growers, compared with the harvest-assist function only. Additionally, for the same ma-

chine price and PAI, the machine would bring more benefits with an increase in harvest productivity because of more savings in labor cost. When the machine price ranges from \$60,000 to \$160,000, PAI ranges from 0% to 20%, and harvest productivity increase ranges from 43% to 63%, the machine's annual net benefit ranges from -\$4,600 to \$105,500. Figure 5 shows that growers can still gain benefits without using the in-field sorting function (i.e., PAI = 0%) when the harvest productivity increase is 43% and the machine is sold at less than \$132,000.

Because the machine was assumed to operate at its full capacity, the labor cost savings are constant for a given harvest productivity increase (table 7). However, the cost savings due to the in-field sorting function are closely related to the PAI, and more savings will be achieved for a higher PAI. Table 7 shows the savings for harvest labor and postharvest handling for harvest productivity increases of 43%, 53%, and 63%. When the PAI is 0%, the savings from in-field sorting are \$0 because no processing apples are sorted out. The PAIs that result in equal savings for harvest labor and

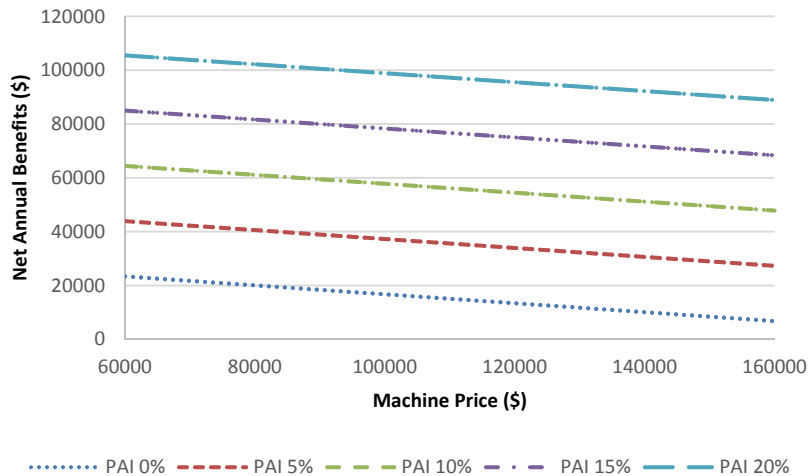


Figure 7. Net annual benefits for fresh apple growers from the apple harvest and sorting machine with 63% harvest productivity increase at different machine prices and processing apple incidences (PAIs). The machine was assumed to run at full capacity of 360 h per season.

Table 7. Net savings for fresh apple growers for different harvest productivity increases with various processing apple incidences (PAIs) when the machine operates at full capacity (values are U.S. dollars).

Harvest Productivity Increase		Processing Apple Incidence				
		0%	5%	10%	15%	20%
43%	Saving on harvest	23,540	23,540	23,540	23,540	23,540
	Saving from sorting	0	18,008	36,016	54,024	72,032
	Total savings	23,540	41,548	59,556	77,564	95,572
53%	Saving on harvest	28,980	28,980	28,980	28,980	28,980
	Saving from sorting	0	19,278	38,556	57,834	77,112
	Total savings	28,980	48,258	67,536	86,814	106,092
63%	Saving on harvest	34,892	34,892	34,892	34,892	34,892
	Saving from sorting	0	20,533	41,065	61,598	82,130
	Total savings	34,892	55,425	75,957	96,490	117,022

postharvest handling are 6.5%, 7.5%, and 8.5% for the harvest productivity increases of 43%, 53%, and 63%, respectively.

BENEFITS FOR PROCESSING APPLE GROWERS

Typically, processing apple growers sell all their apples as processing apples (without sorting). However, these growers could benefit from adopting the machine to sort out fresh apples in-field if the extra revenue generated from the fresh apples outweighed the total costs of the machine and postharvest handling. In the cost-benefit analysis, apples produced by processing apple growers were assumed to be sold entirely as processing apples prior to adoption of the machine. However, with adoption of the machine, processing apple growers can sort out fresh apples from mixed apples in-field, thus generating additional revenue by selling the fresh apples at a much higher price. In this study, it was assumed that 90% of fresh apples are sorted out by the in-field sorting system. Fresh and processing apples were assumed to be sold at \$0.81 kg⁻¹ and \$0.21 kg⁻¹, respectively (Wheat, 2014; USDA, 2015b). Thus, the apple growers can earn an extra \$0.60 kg⁻¹ if fresh apples are segregated from processing apples. Following the same analysis used for fresh apple growers, the net benefits of adopting the machine were calculated for three harvest productivity increases. Figures 8, 9, and 10 summarize the net annual economic benefits (total benefits subtracted by total costs) for processing apple growers for harvest productivity increases of 43%,

53%, and 63%, respectively. When the machine price ranges from \$60,000 to \$160,000 and the PAI ranges from 70% to 100%, the net annual benefit ranges from -\$4,600 to \$120,000. For a given harvest productivity increase and PAI, the net annual benefit decreases with an increase in the machine price. On the other hand, for a given harvest productivity increase and machine price, the machine would bring less benefit with an increase in PAI because fewer fresh apples would be sorted out. When the PAI is 100%, no fresh apples would be sorted out, and the machine would generate cost savings only from the harvest productivity increase.

For a given harvest productivity increase, the labor savings are constant because the machine was assumed to operate at its full capacity. However, the extra benefits from selling the sorted-out fresh apples due to in-field sorting are closely related to PAI, and more benefits will be obtained with a lower PAI because more fresh apples are sorted-out. Table 8 shows the labor savings and benefits of selling the sorted-out fresh apples for harvest productivity increases of 43%, 53%, and 63% at different PAIs. The PAIs that result in equal savings from harvest labor and in-field sorting are 91.7%, 90.5%, and 89.3% for harvest productivity increases of 43%, 53%, and 63%, respectively.

BENEFITS FOR APPLE HARVEST EMPLOYEES

Workers can also benefit from the harvest and in-field sorting machine. When working on the harvest platform, workers do not need to carry buckets, thus reducing the

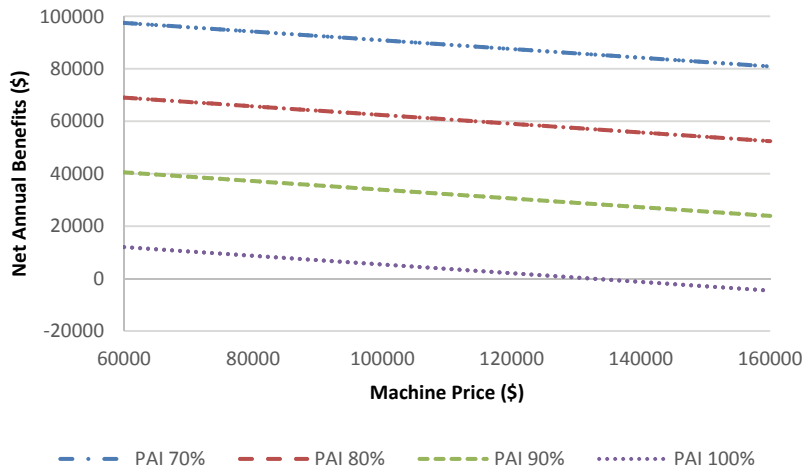


Figure 8. Net annual benefits for processing apple growers from the apple harvest and sorting machine with 43% harvest productivity increase at different machine prices and processing apple incidences (PAIs). The machine was assumed to run at full capacity of 360 h per season.

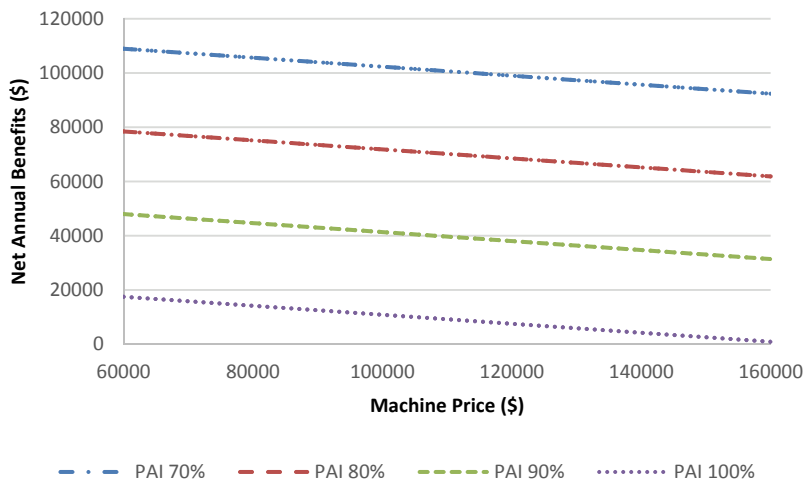


Figure 9. Net annual benefits for processing apple growers from the apple harvest and sorting machine with 53% harvest productivity increase at different machine prices and processing apple incidences (PAIs). The machine was assumed to run at full capacity of 360 h per season.

physical demands and work-related injuries. Many awkward activities, such as stooping to dump apples into the bin and descending ladders with a full bucket, are eliminated, which helps protect the workers from occupational diseases. The machine also eliminates ladder use, and thus ladder-related accidents. By using the harvest platform, workers are less likely to be absent from work due to the occupational diseases that are commonly associated with conventional harvest activities. This will, in turn, increase the workers' income (regardless of whether they are paid on a piece-rate basis or hourly) as well as increase labor availability.

This economic evaluation makes several assumptions that affect the costs and benefits. For example, the machine was assumed to run for 360 h per harvest season (10 h per day, 36 days per season). However, in actual use, the machine may run 12 to 14 h per day with multiple shifts, or 6 to 8 h per day with only one shift. In addition, the real harvest productivity increase may be beyond the conservatively estimated range of 43% to 63%, considering the many innovative features incorporated into the apple harvest and in-field

sorting machine. By using reasonable and conservative assumptions, this study provides guidelines and basic information for machine development and commercialization. Further validation of the economic analysis should be conducted when the machine actually operates in an orchard.

CONCLUSIONS

The economic evaluation conducted in this study showed that adoption of the harvest and in-field sorting machine will increase harvest productivity, thus decreasing harvest labor cost, and achieve cost savings in postharvest storage/grading/packaging for fresh apple growers, while also providing benefits for processing apple growers by allowing them to sell a portion of their harvested apples to the fresh market that would otherwise be destined for processing. After comparison with two commercial harvest platforms, our machine was estimated to increase harvest productivity by 43% to 63%. For fresh apple orchards with processing apple per-

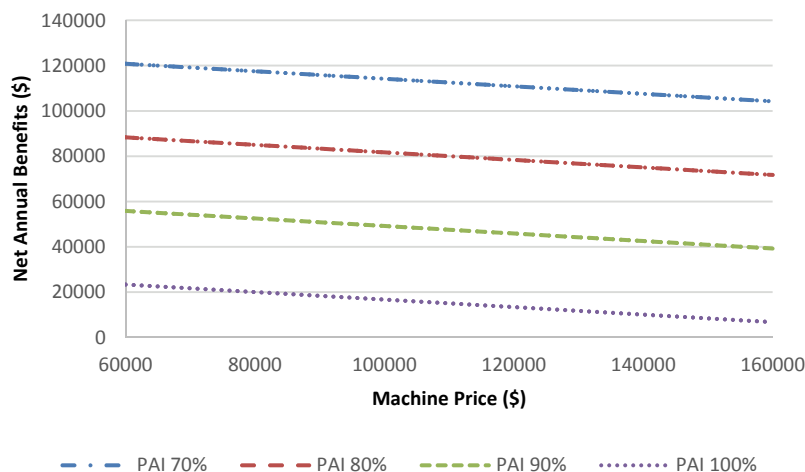


Figure 10. Net annual benefits for processing apple growers from the apple harvest and sorting machine with 63% harvest productivity increase at different machine prices and processing apple incidences (PAIs). The machine was assumed to run at full capacity of 360 h per season.

Table 8. Net savings for processing apple growers for different harvest productivity increases with various processing apple incidences (PAIs) when the machine operates at full capacity (values are U.S. dollars).

Harvest Productivity Increase		Processing Apple Incidence			
		70%	80%	90%	100%
43%	Saving on harvest	23,540	23,540	23,540	23,540
	Saving from sorting	85,486	56,990	28,495	0
	Total savings	109,026	80,530	52,035	23,540
53%	Saving on harvest	28,980	28,980	28,980	28,980
	Saving from sorting	91,514	61,009	30,505	0
	Total savings	120,494	89,989	59,485	28,980
63%	Saving on harvest	34,892	34,892	34,892	34,892
	Saving from sorting	97,469	64,980	32,490	0
	Total savings	132,361	99,872	67,382	34,892

centages of 5% to 15%, the net annual benefit that would accrue from owning a machine ranges from \$13,500 to \$78,400 when the machine price is between \$100,000 and \$160,000 and the machine operates at full capacity. For processing apple orchards with processing apple percentages of 80% to 90% and a machine price between \$100,000 and \$160,000, the net annual benefit ranges from \$23,900 to \$81,700. Overall, the benefits that will be gained from in-field sorting outweigh those gained from the harvest productivity increase. Because harvest-assist and in-field sorting functions are integrated into this machine, apple growers can achieve greater net benefits than with a single-function machine. Adoption of the machine will also improve the harsh working conditions for workers and expand the labor supply, thus helping to alleviate the labor shortage in the apple industry.

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