DEVELOPMENT OF AN AUTOMATED COLOR SORTING SYSTEM FOR RECYCLABLE GLASS CONTAINERS

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ABSTRACT

An automated optical color sorting system for recyclable glass containers has been developed as a full-scale prototype and tested at a materials recovery facility. The system employs five vertical chutes that sort whole clear containers out of a mixed-color stream, and is therefore a separation aid for three color sorting. Tests indicate a 70% success rate at 1.25 ton/hr/chute, while the number of chutes used can be matched to processing needs. The success rate is 100% after both automated and manual sorting have been completed. Each chute has a control circuit with three critical variable parameters that can be adjusted to increase the automated sorter's success rate. A computer simulation and optimization routine have been written to find the optimal combination of the three circuit settings. An economic analysis compares the automated/manual system to an all-manual system and finds a payback period of less than 2 years for a recycling center serving a population of 500,000.

NOMENCLATURE

b = brown or amber glass
C = capital cost of automated bottle sorting system ($)
c = clear or flint glass
$c_{a/ms}$ = overall capacity of the automated/manual system (tons/hour)
CF = cash flow ($)
$chutes$ = number of chutes required
D = annual depreciation of automated bottle sorting system ($)
fpm = feet per minute
fr = single chute feed rate (bottles/second)
g = green or emerald glass
i = inflation rate
lcf = least color fraction
LL = lower limit of the window comparator of the control circuit (V)
LS = labor savings ($)
MRF = material recovery facility
n = number of years (years)
NPV = net present value ($)
$pc_{a/ms}$ = processing cost of the automated/manual system ($/ton)
$pr_{a/ms}$ = overall processing rate of the automated/manual system (bottles/second)
PV = present value ($)
PW = pulse width (msec)
r = interest rate

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S = salvage value of automated bottle sorting system ($)
suc_a = success rate of the automated sorter
t = tax rate
tax = annual tax paid on profits ($)
TL = timing limit of the RC component of the control circuit (V)
UL = upper limit of the window comparator of the control circuit (V)

INTRODUCTION

Recycling makes sense. Limited natural resources are saved, energy consumption is reduced, and air, water and land pollution are cut when recycling substitutes for one-time use. Americans produce approximately 3.5 lb of trash per day, and with glass comprising over 8% of our waste stream (with over half of that being container glass) the importance of glass recycling is clear.

Glass containers are collected through various programs. Some of the more common collection programs include curbside, drop off, buy back, commercial and institutional. Bottles are delivered to a processing facility, commonly referred to as a MRF (material recovery facility), where color sorting, contaminant removal, volume reduction and marketing can take place. A vast majority of glass containers are one of three colors: flint (clear), emerald (green), or amber (brown). In order to meet the marketing requirements of the manufacturers who fill the glass containers, color sorting must occur to high tolerances. Clear glass has a more stringent purity tolerance than green or brown. Clear bottles cannot be produced from brown or green glass.

Manual color sorting of glass is hazardous, slow and expensive, dictating a need for automation. Recognition of this problem was the genesis of this automated clear/color glass container sorting research and development project [1]. The automated sorter is inserted upstream from a manual sorter to separate out most of the clear bottles from the mixed color input glass container stream. The automated system is therefore a separation aid to the manual sorter. In the automated system, containers are elevated, and then descend through an alignment stage as they enter the top of a vertical sensing chute. Free falling through a beam of light, the bottles leave a characteristic trace on an optical sensor. This information passes into an adjustable control circuit, where a yes/no decision is made: divert if clear, or do not divert if nonclear. As a clear bottle exits the bottom of the chute, a diversion gate, actuated by two solenoids, diverts the bottle to the clear input. A nonclear bottle passes by the nonactuated diversion gate to the color output. The two output streams then proceed via horizontal and parallel conveyors to the manual sorter.

An initial laboratory prototype was developed through several iterations of experimentation. When a reasonable level of confidence was gained, a full-scale production prototype was designed, constructed, tested and modified. Trial runs of the full-scale system were completed and compared to an all-manual system to determine economic feasibility.

Many researchers in both industry and academia have attempted to develop an automated recyclable glass container color sorting system, and these projects can be divided by a number of characteristics. Attempts in the 1960s and 1970s to solve this problem focused on cullet color sorting as opposed to whole container sorting [2]. Many recent attempts, including the effort detailed here, follow the whole container approach [3]. At a common sense level, sorting one large piece of glass appears simpler than sorting several small pieces; however, cullet sorting projects attempt to capitalize on preexisting mining and agriculture sorting technology. A second aspect is the sensing approach used. Light reflectance was attempted in the early cullet based systems. A majority of recent and current projects are based on light transmittance, including the subject of this paper. Video imaging is a third approach being investigated in some current projects. A third aspect is the level of automation desired. All systems investigated attempt to completely displace the need for a manual sorter, which differs from the authors' approach of partial automation. By leaving a manual sorter in the system, an overall success rate approaching 100% can be realized, while the manual sorters processing rate will be greatly increased with the addition of the automated sorter.

Three factors determine the feasibility of a bottle color sorting system: *(a)* success rate; *(b)* feed rate; and *(c)* cost (both initial capital investment and operating cost). The success rate is a constraint determined by the buyer of the color sorted cullet (i.e., a glass furnace operator). Purity levels of 99% and greater are often demanded for flint cullet, while green and amber are only slightly less stringent. If a sorting system does not meet this constraint, then it fails. The feed rate is a constraint determined by the glass container processor, which is often a MRF. The feed rate must be fast enough to adequately process the volumes of glass that the MRF wants to handle in a given period of time. Cost, the third factor, entails the initial capital investment of the sorting system purchaser, and the continuous operating cost of that system. Power requirements

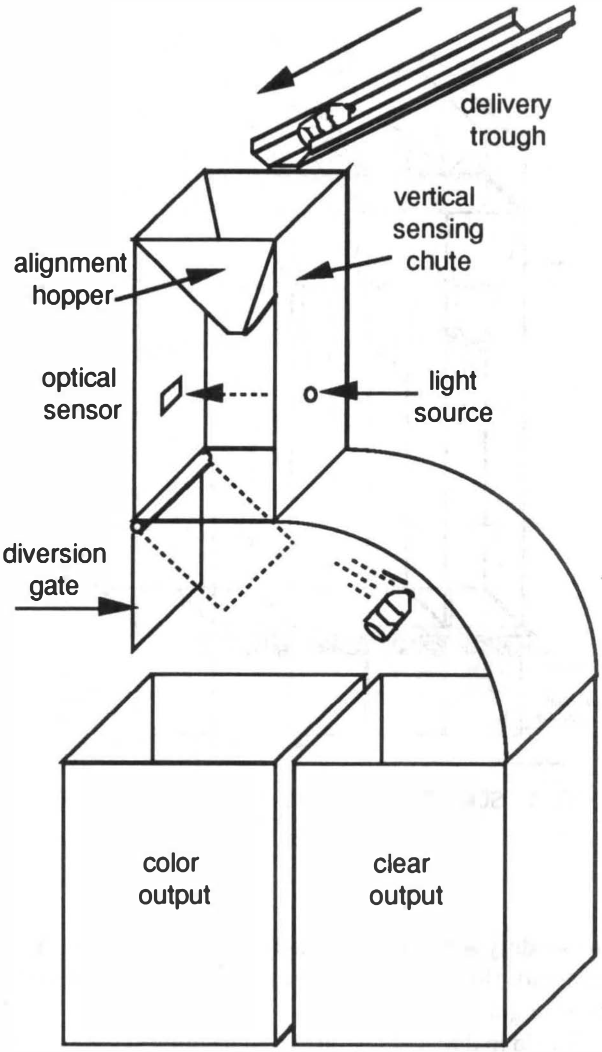

FIG. 1 SCHEMATIC OF THE LABORATORY PROTOTYPE

of most systems investigated are minimal, so the major continuous cost to be considered is labor.

APPARATUS

Laboratory Prototype

In order to test the initial hypothesis, that is, glass containers can be optically differentiated by color and then mechanically sorted, a first generation laboratory prototype (Fig. 1) was constructed. Glass containers enter the system via a downward sloping trough, and enter a vertical sensing chute with an 8-in. square opening. Located at the top entrance of the chute is a 15-in. long spring-loaded and hinged alignment hopper.

A red, high intensity light emitting diode (LED) [luminous intensity = 500 millicandles (mcd)] functions as the light source, providing a narrow, focused, steady beam of light, while drawing very little current [maximum continuous forward current = 50 milliAmperes (mA) and maximum forward voltage at 20 mA = 2.5 V], and having a very long life (approximately 10,000 hr).

Initially, various photoresistors were tested as sensors, finally settling on a cadmium sulfide photo cell with a surface area of 0.45 square centimeters (cm^2). Due to a slow time response, the photocell was replaced with a photovoltaic sensor. Two were examined: *(a)* a flexible amorphous silicon solar cell; and *(b)* a polycrystalline rigid silicon solar cell. The second sensor was selected over the first for its greater voltage output, and is superior over the photoresistor in two primary regards: *(a)* a larger surface area (8 cm^2); and *(b)* a quicker time response. The sensor used has a maximum voltage rating of 0.55 V, and maximum current rating of 0.3 A.

Production Prototype

The full-scale production prototype system is composed of five parallel vertical sensing chutes, and has been tested at a MRF, the Community Recycling Center (CRC), Champaign, Illinois. A schematic of the automated/manual system is shown in Fig. 2. The overall dimensions of the system are: height 11 ft (3.35 m), width 4 ft 7 in. (1.40 m), depth 2 ft 8 in. (0.81 m). Bottles travel up the 45 deg. inclined input conveyor at 60 fpm (0.30 m/s). The containers fall onto the trough ramp and bounce and slide through the five troughs (Fig. 3). The bottles then pass through the alignment hoppers which serve three purposes: *(a)* vertical alignment of the bottles; *(b)* centering of the bottles so that they pass through the light beam; and *(c)* speed reduction of the bottles to facilitate a longer sensor reading. The bottles then pass through the light beams and the light transmittance is sensed and passed on to the control circuits. A high intensity red LED with a luminous intensity of 2000 mcd is used as the light source, and a silicon solar cell (2 cm by 4 cm) acts as the sensor, as in the laboratory prototype.

Figure 4 displays the information flow through the circuit. Initially, the signal from the solar cell must be amplified from the millivolt level to a 10 V level. This is accomplished by an instrumentation amplifier with an adjustable gain, which also acts to filter out noise. The amplified signal feeds directly into a window comparator which used two op amps. One compares the signal to the upper limit (*UL*) and the other checks

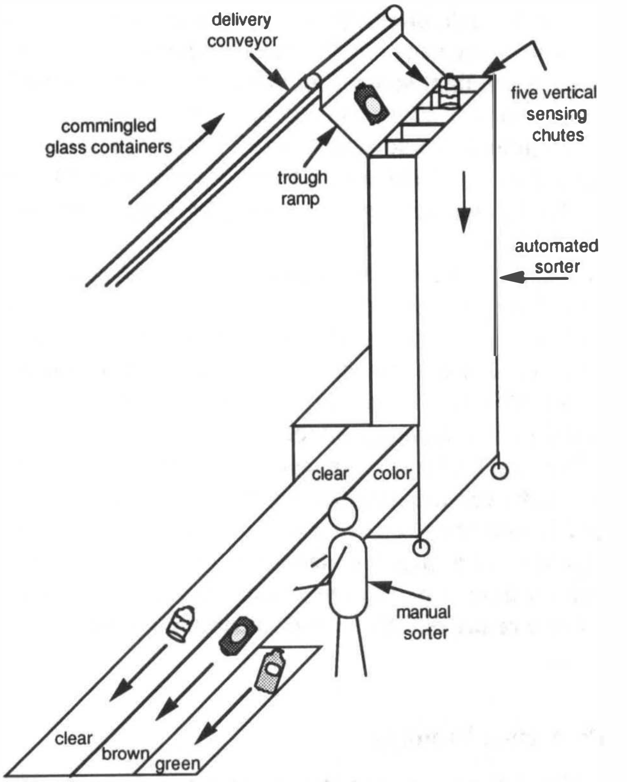

FIG. 2 SCHEMATIC OF THE AUTOMATED SORTER IN LINE WITH A MANUAL SORTER

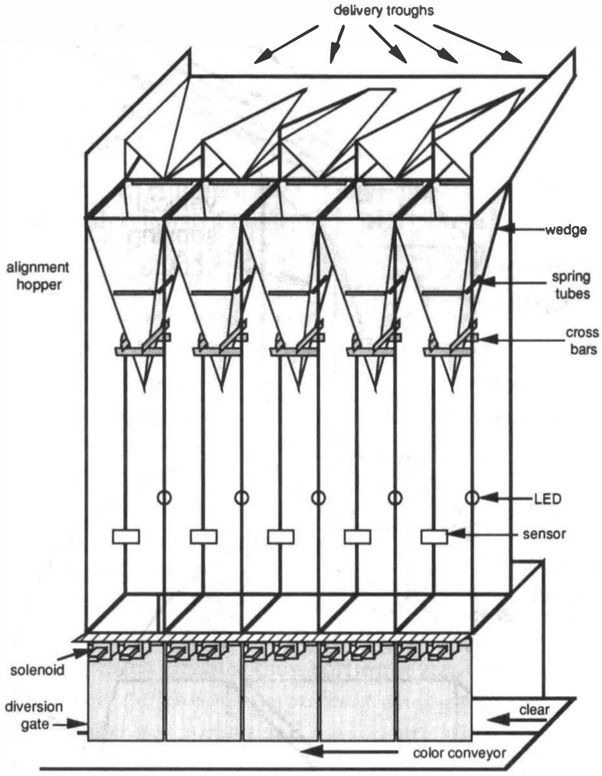

FIG. 3 SCHEMATIC OF THE ALIGNMENT, SENSING AND DIVERSION SECTIONS

against the lower limit (*LL*). The limits are adjustable with individual variable resistors. The signal then flows to a transistor acting as a switch. The output of the window comparator is therefore either high or low. This on/off signal feeds into an RC (resistor/capacitor) component. When the incoming signal steps up from zero to the high value, the RC begins to build exponentially. When the signal drops back to zero, the RC output decays exponentially toward zero. The output of the RC component flows into a single comparator and is checked against an adjustable timing limit (*TL*). If the limit is exceeded, the usually high output of the comparator steps down to zero until the limit is no longer exceeded. This falling edge is needed to trigger the next component, a 556 timer chip. When triggered, the 556 sends out a positive pulse of adjustable width (*PW*). This pulse flows into an npn Darlington transistor array. When the pulse for a clear signal flows into the base of the transistor, a +12 V pulse of equal duration coming directly from the power supply flows to a solid state relay. The relay is optically isolated with a triac. When triggered, the relay closes its internal switch on an AC line. This 115 VAC pulse flows to two heavy-duty solenoids that each have a 1-in. travel. The solenoids then act to swing out a diversion gate thereby diverting a clear container.

To aid in data collection and in locating system problems, LCD counters and indicator LEDs were added to the production prototype control box. Each chute has two counters, a counter reset button, and two LEDs. One counter sums the number of diversion signals produced by the circuit. This number ideally should match the number of clear bottles in a batch of containers processed. A green LED turns on with each diversion. The other counter sums the total number of containers that pass through its corresponding chute. A red LED flickers a number of times, with each disruption of the light beam on the sensor yielding a "bottle in the chute" indication.

Experiment Results

In an effort to determine the feasibility of the automated/manual sorting system, tests were performed to ascertain the success rate at various feed rates using the full-scale prototype at CRC. Experiments were completed using one, three, four and five chutes. In addition

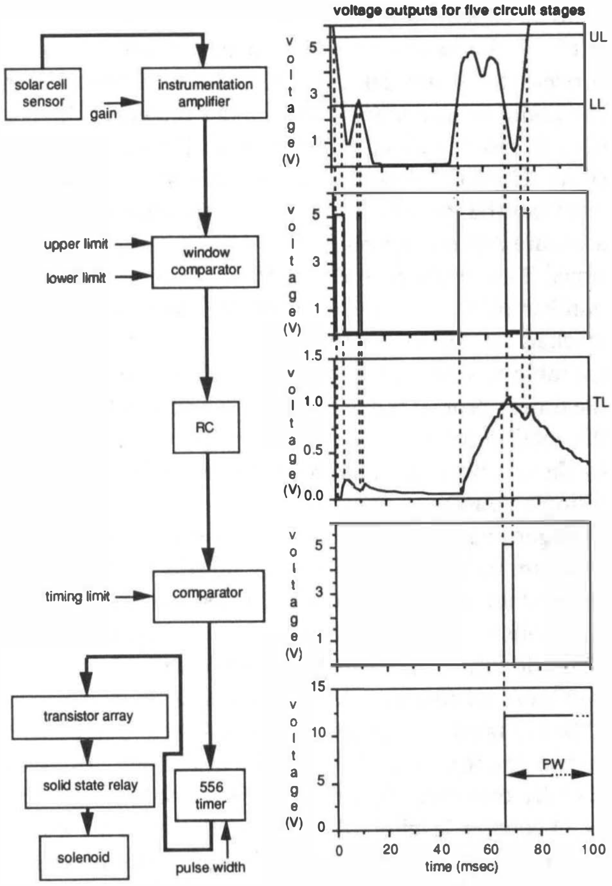

FIG. 4 CIRCUIT BLOCK DIAGRAM AND CORRESPONDING COMPONENT OUTPUT GRAPHS

to varying the feed rate, the color mix of the input stream was also varied.

Figure 5 shows the actual success rates of many of the trials as a function of the feed rate. The feed rate is a rough estimate. The input conveyor delivers one cleat of bottles per second, thus the manually controlled number of bottles per cleat was divided by the number of chutes operating in a given test to arrive at the feed rate (bottle/second/chute). The results show a decreasing accuracy trend when the feed rate increases. This is to be expected as the sensor receives less information per bottle at a faster feed rate. Nonclear results were always more successful than clear results, meaning that the circuits were set conservatively so as not to divert color bottles into the clear stream. The scatter in the data is due to the relatively small sample size (*n*) of some trials, and the better performance of the 5 chute test may be linked to its unrecorded input color mix. Additionally, various circuit settings (*UL, LL, TL, PW*) were used throughout the tests.

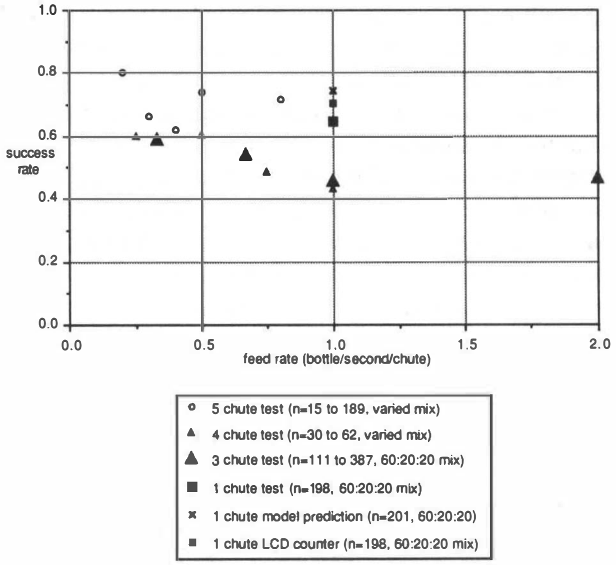

FIG. 5 SUCCESS RATE AS A FUNCTION OF FEED RATE FOR ALL OF THE HIGH VOLUME GLASS TESTS

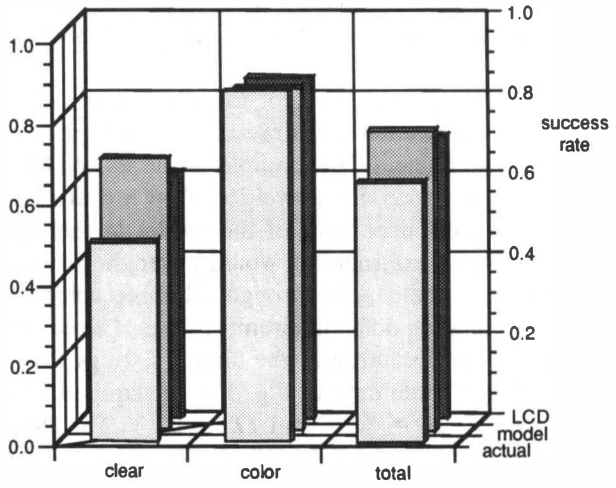

FIG. 6 SUCCESS RATES FROM A SINGLE CHUTE TRIAL AT ONE BOTTLE PER SECOND FOR THE ACTUAL OUTPUT, THE COMPUTER MODEL AND THE LCD COUNTERS

Figure 6 displays results from one of a series of data acquisition tests performed on individual chutes. Data acquisition hardware was attached to the output of the instrumentation amplifier on the control circuit, and it recorded the amplified sensor output for individual bottles. Roughly 200 bottles with a 60% clear, 20% green, 20% brown mix were used in each test, and each chute was tested twice. In addition to the sensor traces, the actual output count was recorded as were the LCD totals. The digitized sensor traces were then used as input data for a computer coded mathematical model of the control circuit. The output of the computer simulation is the success rate at the supplied circuit settings. Figure 6 compares the three versions of the results of one of the tests for chute 3. The computer simulation is also used as the foundation of a search routine that attempts to find the optimal combination of circuit settings (*UL, LL, TL*). The general conclusion of a larger number of search trials was that the circuit was fairly impervious to minor changes in the settings, most likely due to the variable nature of the bottle stream and bottle configuration in free fall past the sensor.

The actual values of the success rates of the multiple chute trials are lower than anticipated. This expectation is based on the previous single chute trials that employed a more controlled delivery of containers. In Fig. 6, 119 clear, 39 green and 40 brown bottles were passed through the chute at approximately one bottle per cleat (one bottle/second/chute). An actual overall success rate of 65% was realized (50% clear, 87% color). This is significantly greater than the 45% success rates at one bottle/sec realized from the multi-chute trial shown in Fig. 5.

Three immediate reasons for this discrepancy arise. The first is the possibility of dramatically different sample sets of containers. For example, if one set had been stored outside on a dry gravel lot, then a coating of dust could exist over most of the bottles in that set. This coating of external dirt would lower the amount of light that could pass through all three colors of glass necessitating different circuit settings. The second possibility revolves around the circuit settings themselves. The 3 chute data in Fig. 5 were acquired with $UL = 7.6$ V, $LL = 3.1$ V and $TL = 2.1$ V. The chute 3 data in Fig. 6 used $UL = 7.0$ V, $LL = 3.7$ and $TL = 2.3$ V. The second set of data has a lower window of similar height, and a longer timing limit. The third factor involves bottle interaction. In the multi-chute tests, three bottles were on each cleat and passed through the trough section together. Possibly two or even three of the containers could have traveled down one chute, resulting in a doubled or tripled (respectively) feed rate. Even if the three bottles reached individual chutes, their interactions with each other coming off of the conveyor and entering the chutes could increase or decrease the speed of a given bottle. If the bottle is delayed, then a bottle from the next cleat (if not delayed itself) will be less than one second behind the first one. And, as Fig. 5 shows, decreasing the spacing between bottles decreases the success rate.

Some potential room for improvement is indicated in Fig. 6. As the graph shows, a strong correlation exists between the computer model and the actual results for the nonclear containers. The model predicts a higher success rate for clear, however, than the actual results show. The LCD counter's clear success rate is slightly less than the model prediction, and the counters are an accurate representation of the actual attempted diversions. This leads to the conclusion that a significant number of clear bottles are detected as clear, but the mechanical diversion system does not divert all of these containers. The central problem here lies in timing. If the timing problems can be addressed successfully, then the total success rate could rise to the level predicted by the computer simulation (65% at one bottle/sec for a single chute).

Regarding the system's optimal overall success rate as a function of feed rate, 56% success at 0.5 bottle/second/chute appears to be the best result from the high volume, multiple chute tests. If the negative effects of bottle interaction can be reduced, then the success rate can potentially rise to the single chute level of 65% at 1 bottle/sec (approximately 1.25 ton/hr or 1.13 metric ton/h). If each bottle identified as clear was actually diverted, then the accuracy could rise to the LCD counter level of 70% at 1 bottle/sec. This would require improvements in the timing of the diversion section. Finally, if the real system fit the predictions of the mathematical model, then the success rate would rise to 74% at 1 bottle/sec. This could be accomplished by using electronic components with tighter tolerances which would provide more accurately known values to be used in the model. Improvements in the model would lower the predicted success rate by bringing the model more in line with the actual system.

These results show a lower success rate than previously run laboratory prototype tests, where single containers were dropped down the single chute and diversions were recorded. Circuit settings were chosen by experimentation and intuition. Twenty-six bottles were dropped individually, 20 times each (half bottom first, half top first), totalling 520 samples. The success rates for clear, color and total were 76%, 91% and 83% respectively, for a 58% clear to 42% color ratio.

In another laboratory prototype test, bottles were continually fed through the system. The overall success rate was 87% for a 61% clear to 39% color input ratio. Feed rates of 0.58–1.85 bottles/sec were observed translating to a range of 993–3591 lb/hr for one chute (450–1630 kg/h/chute). Success rates varied from 43.3% to 87.2% for all of the tests completed on both systems.

ANALYSIS

Additional information regarding the incoming glass stream color composition and the manual sorting processing rate was collected. Surveys of the various collection programs of the Community Recycling Center showed that the color ratio varies across collection programs, neighborhoods, seasons and other factors. The residential trials varied between 50% and 67% clear with the remainder split between green and brown. Commercial loads varied between 10% and 25% clear. An average bottle mass was determined to be 0.7 lb (318 g).

In an all-manual system the manual sorter addresses a single input stream of mixed color containers and sorts out the two lesser fractions into their individual outputs. In this way the largest fraction is negatively sorted minimizing the labor required. Manual processing speed was determined to be a function of five primary variables: *(a)* fraction of bottle stream requiring a positive sort; *(b)* ratio of the two lesser color fractions to each other; *(c)* stream density; *(d)* effort of the manual sorter; and *(e)* capability of the manual sorter. Assuming an overall fraction sorted of 20–60% and a sustainable work effort for a capable sorter, a 1 bottle/sec sorting rate is assumed for the analysis. This translated to an all-manual system processing rate of 2.5 bottles/sec (assuming a 60/20/20 clear/green/brown ratio), because a majority of the stream (60%) is negatively sorted. This is equivalent to 3.15 tons/hr. Assuming a population of 500,000 in a community served by a single MRF with a recovery rate of 25%, approximately 25,000 tons (22,680 t) of container glass will be recycled annually. Assuming a labor rate of \$10/hr to support a manual sorter, an annual labor cost of \$19,841 would result (\$3.17/ton).

Working as a separation aid, the automated clear/color sorting system is designed to reduce the person-hours required to process a given capacity of glass containers. This is accomplished by reducing the number of physical separations that the manual sorter must perform while maintaining a sufficiently high feed rate for the manual sorter. The automated sorter splits the incoming three color stream into two fractions: one primarily clear, the other primarily green and brown. The manual sorter then sorts brown (or green) from the green/brown stream, and must also sort nondiverted clear bottles into the clear stream and incorrectly diverted nonclear bottles from the clear conveyor to the green or brown output. Despite the success rate of the automated sorter, the finished product of the total sorting process will be three bins of color sorted cullet approaching 100% color purity, due to the manual sorter addressing the output of the automated sorter.

The two primary costs associated with the automated/manual system are capital equipment costs and labor costs. Cost of an automated sorter has not been determined exactly, but a range of \$1000–\$30,000 has been estimated for a 2- to 20-chute system. This initial capital cost must be offset by labor savings realized over the useful life of the automated system for it to be economically feasible.

The automated system is of modular design, allowing the user to specify the number of vertical sensing/diversion chutes to match the processing needs of the given facility. Calculating the number of chutes required (*chutes*) depends on the manual sorting speed, the empirical success rate of the automated sorter (suc_a) and the chute feed rate (fr). In equation form:

$$suc_a = -0.2(fr) + 0.90 \tag{1}$$

$$chutes = \frac{sr_m}{[(1 - suc_a) + suc_a(lcf)](fr)} \quad \{\text{round up}\} \tag{2}$$

where lcf is least color fraction (20% for either green or brown in the current example). The example is continued with the following performance estimates of the automated sorter:

$$\text{manual sorting rate} \approx 1.0 \text{ bottle/sec}$$

$$fr \approx 1.0 \text{ bottle/sec/chute}$$

$$suc_a = -0.2(1.0) + 0.90 = 70\%$$

$$chutes = \frac{1.0 \text{ bottle/sec}}{[(1 - 0.70) + 0.70(0.20)]\ (1.0 \text{ bottle/sec/chute})} = 2.3 \text{ chutes}$$

$$\because chutes = 3 \text{ chutes required}$$

Since Eq. (2) does not equal an integer number of chutes, a slower feed rate must be calculated with the rounded up integer number of chutes:

$$fr = \frac{sr_m}{[(1 - suc_a) + suc_a(lcf)](chutes)} \tag{3}$$

$$fr = \frac{1.0 \text{ bottle/sec}}{[(1 - 0.70) + 0.70(0.20)](3 \text{ chutes})} = 0.76 \text{ bottle/sec/chute}$$

This allows an increase in the success rate of the automated sorter to be calculated using Eq. (4). The new feed and success rates are then used in calculating the automated/manual system's processing rate and capacity.

$$suc_a = -0.2(0.76 \text{ bottle/sec/chute}) + 0.90 \qquad (4)$$

$$= 75\%$$

The number of chutes required by Eq. (2) is not a function of the overall capacity of a MRF, but rather calibrates the processing and success rates of the automated sorter to match the manual sorter's speed. In this way the manual sorter is not forced to stand idle or stop the processing line to catch up.

The overall capacity of the automated/manual system is a function of the number of chutes, feed rate, success rate, manual sorting rate and glass input stream color composition.

$$pr_{a/ms} = (fr)(chutes) \qquad (5)$$

$$c_{a/ms} = (pr_{a/ms})\left(\frac{\text{mass}}{\text{bottle}}\right)\left(\frac{1 \text{ ton}}{2000 \text{ lb}}\right)\left(\frac{3600 \text{ sec}}{1 \text{ hr}}\right) \qquad (6)$$

Continuing the example:

$$pr_{a/ms} = (0.76 \text{ bottle/sec})(3 \text{ chutes}) = 2.3 \text{ bottles/sec}$$

$$c_{a/ms} = \left(\frac{2.3 \text{ bottles}}{\text{sec}}\right)\left(\frac{0.7 \text{ lb}}{\text{bottle}}\right)\left(\frac{1 \text{ ton}}{2000 \text{ lb}}\right)\left(\frac{3600 \text{ sec}}{1 \text{ hr}}\right)$$

$$= 2.86 \text{ ton/hr}$$

A community of 500,000 persons with a 25% recovery rate is now examined to continue the current example. For a typical curbside load of glass (60% clear, 20% green, 20% brown), the manual sorter works at one bottle per second in conjunction with the three-chute automated sorter with an input speed of 0.76 bottle/sec/chute. At an average mass of 0.7 lb/bottle, the automated/manual system sorts 2.86 ton/hr. At that rate, 2185 person-hours (approximately 7 hr/week) would be needed to process the annual amount of glass recovered (6250 tons). At the labor rate of \$10/hr, this would result in an annual labor cost of \$21,825, and a processing cost of \$1.75/ton.

$$\text{labor hours}_{a/ms} = \frac{(\text{glass recovered})}{c_{a/ms}} \qquad (7)$$

Equation (7) is in annual terms. One shift for a single manual sorter totals 2080 hr/year, and two shifts total 4160 hr/year. If labor hours$_{a/ms}$ exceeds 2080 hr, then additional sorters, a second shift or both can be added. Chutes may be added in clusters of the number calculated in Eq. (2) (one cluster per each additional manual sorter). This will increase the actual number of chutes so that the total labor value approaches but does not exceed 2080 or 4160 hr/year. Equation (8) calculates the number of clusters of chutes depending upon if one or two shifts are used. In Eq. (9) and (10) "chutes" refers to the rounded up integer number of chutes needed as calculated using Eq. (2).

$$\text{number of clusters of chutes} = \frac{\text{labor hours}_{a/ms}}{2080 \text{ or } 4160} \text{(round up)} \qquad (8)$$

$$\text{actual number of chutes} = (\text{chutes})(\text{number of clusters of chutes}) \qquad (9)$$

$$\text{number of manual sorters} = \frac{\text{actual number of chutes}}{\text{chutes}} \text{(round up)} \qquad (10)$$

$$\text{labor cost}_{a/ms} = (\text{labor hours}_{a/ms})(\text{labor rate}) \qquad (11)$$

Equations (5) and (6) which are dependent on the number of chutes used, must be recalculated before the processing cost of the automated/manual system ($pc_{a/ms}$) can be calculated:

$$\text{actual } pr_{a/ms} = (\text{actual number of chutes})(fr) \qquad (12)$$

$$\text{actual } c_{a/ms} = (\text{actual } pr_{a/ms})\left(\frac{\text{mass}}{\text{bottle}}\right)\left(\frac{1 \text{ ton}}{2000 \text{ lb}}\right)\left(\frac{3600 \text{ sec}}{1 \text{ hr}}\right) \qquad (13)$$

$$pc_{a/ms} = \frac{\text{labor rate}}{\text{actual } c_{a/ms}} \qquad (14)$$

$$\text{labor hours}_{a/ms} = \frac{(6250 \text{ ton/year})}{(2.86 \text{ ton/hr})} = 2185 \text{ person-hr/year}$$

$$\text{number of clusters of chutes} = \frac{2185 \text{ person-hr/year}}{2080 \text{ person-hr/year}}$$

$$= 2 \text{ clusters}$$

$$\text{actual number of chutes} = (3)(2) = 6 \text{ chutes}$$

$$\text{number of manual sorters} = \frac{6\ \text{chutes}}{3\ \text{chutes}} = 2\ \text{manual sorters}$$

$$\text{labor cost}_{a/ms} = \left(\frac{\$10}{\text{hr}}\right)(2{,}183\ \text{person-hr}) = \$21{,}830$$

$$\text{actual } pr_{a/ms} = (6\ \text{chutes})(0.76\ \text{bottle/sec/chute})$$

$$= 4.5\ \text{bottles/sec}$$

$$\text{actual } c_{a/ms} = 4.5\ \frac{\text{bottles}}{\text{sec}}\left(\frac{0.7\ \text{lb}}{\text{bottle}}\right)\left(\frac{1\ \text{ton}}{2000\ \text{lb}}\right)\left(\frac{3600\ \text{sec}}{1\ \text{hr}}\right)$$

$$= 5.73\ \frac{\text{ton}}{\text{hr}}$$

$$pc_{a/ms} = \frac{\$10/\text{hr}}{5.73\ \text{ton/hr}} = \$1.75/\text{ton}$$

This example yields a 10% negative savings in labor hours when using the automated sorter, or a $1984 loss in labor costs.

An annual cash flow (*CF*), over the life of the machine, must be compared to the capital cost of the automated system. This comparison incorporates the labor cost savings (*LS*), annual straight-line depreciation of the automated system (*D*), the capital cost of the machine (*C*), its salvage value at the end of its useful life (*S*), the tax rate of the firm buying the sorter (*t*), the inflation rate (*i*), the interest rate (*r*) and the number of years of the life of the system (*n*). Power costs are assumed negligible for the automated sorter, as the main power draw will be from the infeed conveyor, which is also required in the all-manual case. The overall present value (*PV*) benefits of purchasing the system less its costs is the net present value of the machine (*NPV*). An *NPV* greater than or equal to zero indicates a financially attractive project.

$$NPV = (PV \text{ of system's } CF \text{ benefits}) - (PV \text{ of system's costs}) \qquad (15)$$

$$PV_{CF} = CF\left[\frac{1 - \dfrac{(1+i)^n}{(1+r)^n}}{\dfrac{(1+r)}{(1+i)} - 1}\right] \qquad (16)$$

$$PV_{cost} = C - S \qquad (17)$$

$$D = \frac{C - S}{n} \qquad (18)$$

$$tax = (LS - D)t \qquad (19)$$

$$CF = (LS - D) - tax + D = (LS - D)(1 - t) + D = LS - tax \qquad (20)$$

$$NPV = \left[\left(LS - \frac{C-S}{n}\right)(1 - t) + \frac{C-S}{n}\right]\left[\frac{1 - \dfrac{(1+i)^n}{(1+r)^n}}{\dfrac{(1+r)}{(1+i)} - 1}\right] - (C - S) \qquad (21)$$

The amount of tax calculated in Eq. (18) holds to be accurate even if the labor savings (*LS*) is negative because it is assumed that the MRF will add this loss in with all of its other projects, and the corporate tax rate will be applied at that time.

Following through with the ongoing example, assuming $C = \$2{,}000$, $S = \$500$, $t = 34\%$, $i = 4\%$, $r = 10\%$, $n = 5$ years and $LS = \$397$, the *NPV* on the project is −$6619, indicating a poor investment. If, however, the color ratio in a community was 50/25/25 (clear/green/brown), then the *NPV* would be $2402 with a 1.34 year payback period (Table 1).

Table 1 shows the results of the economic analysis for community sizes of 100,000, 500,000, 1 million and 5 million people for four different clear/green/brown ratios. The *NPV* is calculated based on a 5-year life of the automated system. A positive *NPV* indicates a financially beneficial project, while a negative value reveals a disadvantageous project. The payback period is the number of years required to realize a return on the initial investment (INF indicates an infinite payback period). All of the other assumptions stated immediately above were used in calculating Table 1 (i.e., $C = \$2000$, $S = \$500$, $t = 34\%$, $i = 4\%$, $r = 10\%$, recovery rate = 25%, labor rate = $10/hr, and manual sorting rate = 1.0 bottle/sec), except that the cost of the system is estimated at $4000 for the 15- to 20-chute size. It is assumed that nonsorting time of a manual sorter can be filled with other unrelated MRF activities.

A shorter payback period is realized when the color mix approaches equilibrium (i.e., one-third each). This is due to the reduced level of the negatively sorted fraction in the manual sorting system comparison, that is, the automated sorter displaces the greatest amount of labor in this case. Also, the larger the population of

TABLE 1 ECONOMIC COMPARISON OF INCREASING POPULATIONS FOR DIFFERENT CLEAR/GREEN/BROWN RATIOS FOR A SUCCESS RATE OF 70% AT A BEGINNING FEED RATE OF 1.0 BOTTLE/sec/CHUTE

glass collected			population	no. of	no. of manual	labor (person-	system capacity		payback period
c	g	b	(persons)	chutes	sorters	hours/yr.)	(tons/hr.)	NPV	(years)
67%	17%	17%	100,000	3	1	413	3.02	-$3,381	INF
60%	20%	20%	100,000	3	1	437	2.86	-$2,178	INF
50%	25%	25%	100,000	3	1	471	2.65	-$374	8.84
20%	40%	40%	100,000	2	1	575	2.17	-$513	12.50
67%	17%	17%	500,000	3	1	2067	3.02	-$12,632	INF
60%	20%	20%	500,000	6	2	2183	5.73	-$6,619	INF
50%	25%	25%	500,000	6	2	2356	5.31	$2,402	1.34
20%	40%	40%	500,000	4	2	2877	4.34	$1,708	1.70
67%	17%	17%	1,000,000	3	1	4134	3.02	-$24,197	INF
60%	20%	20%	1,000,000	6	2	4365	5.73	-$12,170	INF
50%	25%	25%	1,000,000	6	2	4712	5.31	$5,871	0.65
20%	40%	40%	1,000,000	4	2	5754	4.34	$4,483	0.82
67%	17%	17%	5,000,000	15	5	20668	15.12	-$118,137	INF
60%	20%	20%	5,000,000	18	6	21825	17.18	-$58,001	INF
50%	25%	25%	5,000,000	18	6	23562	15.92	$32,203	0.30
20%	40%	40%	5,000,000	14	7	28770	15.21	$25,264	0.38

an area served by a MRF with an automated sorting system, the shorter the payback period. One shift of labor (2080 hr/year) could be used in the two smaller size communities, while two shifts (4160 hr/year) would be needed for the two larger cities. Also noteworthy is the fact that the greater the utilization of the automated system, the shorter the payback period.

The best opportunity for improving the economics of the system is to increase its success rate through improved material handling. Table 2 shows the results for the same parameters as Table 1 except for an improvement in the success rate of the automated system. The previous example assumed a success rate of 70% at a feed rate of 1.0 bottle/sec/chute, while Table 2 assumes a success rate of 80% at the same feed rate.

CONCLUSIONS

System cost, feed rate and success rate are the three critical factors in evaluating a glass container color sorting system. At a cost of approximately $2000 for a 1–4 chute system plus labor, a feed rate of 1.25 ton/hr/chute, and a 100% success rate, the automated/manual system has potential. A number of physical improvements of the full-scale prototype, including bottle alignment, spacing and timing are planned to be incorporated into a demonstration unit that will be designed as part of a complete glass processing system (as opposed to the retrofit approach used for the production prototype). These improvements will increase the success rate of the automated sorter, thereby increasing the feed rate of the system, reducing the labor hours required and reducing the payback period. The system is recommended for an intermediate processing facility, as opposed to a glass manufacturing plant. As quality constraints rise, the cullet sorting approach appears to be less feasible. Increased handling increases bottle breakage, thus suggesting that color sorting occur as close to the generator (i.e., the consumer) as possible.

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TABLE 2 ECONOMIC COMPARISON OF INCREASING POPULATIONS FOR DIFFERENT CLEAR/GREEN/BROWN RATIOS FOR A SUCCESS RATE OF 80% AT A BEGINNING FEED RATE OF 1.0 BOTTLE/SECOND/CHUTE

glass collected			population	no. of	no. of manual	labor (person-	system capacity		payback period
c	g	b	(persons)	chutes	sorters	hours/yr.)	(tons/hr.)	NPV	(years)
67%	17%	17%	100,000	3	1	331	3.78	-$1,068	INF
60%	20%	20%	100,000	3	1	357	3.50	$43	4.77
50%	25%	25%	100,000	3	1	397	3.15	$1,708	1.70
20%	40%	40%	100,000	2	1	516	2.42	$1,153	2.16
67%	17%	17%	500,000	3	1	1653	3.78	-$1,068	INF
60%	20%	20%	500,000	3	1	1786	3.50	$4,483	0.82
50%	25%	25%	500,000	3	1	1984	3.15	$12,810	0.32
20%	40%	40%	500,000	4	2	2579	4.85	$10,034	0.41
67%	17%	17%	1,000,000	3	1	3307	3.78	-$1,068	INF
60%	20%	20%	1,000,000	3	1	3571	3.50	$10,034	0.41
50%	25%	25%	1,000,000	3	1	3968	3.15	$26,687	0.16
20%	40%	40%	1,000,000	4	2	5159	4.85	$21,136	0.20
67%	17%	17%	5,000,000	12	4	16534	15.12	-$2,491	INF
60%	20%	20%	5,000,000	15	5	17857	17.50	$53,019	0.19
50%	25%	25%	5,000,000	15	5	19841	15.75	$136,284	0.08
20%	40%	40%	5,000,000	14	7	25794	16.96	$108,529	0.10

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