OPTIMIZATION OF MILLING PERFORMANCE OF A SUGAR MILL BY USING LINEAR PROGRAMMING TECHNIQUE

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The proposed study was carried out at Pahrianwali Sugar Mills, Lalian District Jhang. Data was collected for sugar lost and moisture content in bagasse at different milling parameters like mills settings, cane imbibition, hydraulic pressure on top rollers of the mills and index of cane preparation separately. This data was used to develop constraint equations for linear programming model. An objective function of linear programming (LP) model was also developed to minimize the cost of steam production and sugar lost in bagasse. Quantitative System Business (QSB) software was used to solve the linear programming model. The results of the LP model indicated an optimum cane crushing capacity of 5000 tons/day for mill setting of 58.3 mm against a hydraulic pressure of 0.225 x 10^3 kg/cm² to earn maximum profit of Rs. 58312/hr.

Keywords: Sugar mill, linear programming, mill setting, imbibition, bagasse

INTRODUCTION

Sugar industry is one of the major agro-based industries that is playing a vital role in the development of our country. The cane-sugar industry is one of the oldest industries in Pakistan and is running with traditional management and technology. Milling performance of majority of the sugar mills in Pakistan is much below the national and international standards. Normal sugar extraction of about 90% appears to be satisfactory, however, this reflects that 8% sugar in the cane is lost to bagasse that is burnt as a fuel in the boilers. Hence, updating is absolutely necessary in every section of sugar industry especially in milling/crushing section which is responsible to control all the major losses of a sugar mill (Azeem, 1976).

It therefore, becomes extremely important to reduce this loss by optimally using the available resources. There are many important factors that determine the overall performance of the milling train. An optimal mill setting under prevailing resources was the main object of this study. To achieve this objective, the study was designed to construct linear programming model for Pahrianwali Sugar Mills Limited. The model aimed at minimizing the milling losses and cost.

MATERIALS AND METHODS

The Pahrianwali Sugar Mills consists of mainly cane preparation unit, milling train, juice processing unit, centrifugation and sugar drying units. Two bagasse cum furnace oil boilers are used to generate super heated steam at the rate of 120 tons/hr to run 500-1500 kW steam turbines installed for cane preparation and milling units. The rate of steam consumption mainly depends upon the cane preparation index, pressure on top roller on milling train and imbibition (addition of water to prepared cane).

Development of objective function

The following objective function was developed to minimize the milling losses in the form of sugar (pol) lost to bagasse, furnace oil consumed in the boilers due to moisture in bagasse and extra steam consumption due to changing levels of imbibition, hydraulic pressure and index of cane preparation at constant crushing rate.

Min Z = C₁ X + C₂ I + C₃ P + C₄ D

Where

I, P and D are decision variables and C₁, C₂, C₃ and C₄ are the co-efficient of objective function

X = 1

I = Index of cane preparation

P = Hydraulic pressure on top rollers of the mills (10³ x kg/hr)

D = Weight of imbibition per unit weight of cane (kg/kg)

Mathematically, this may be expanded to include.

Min Z = 1068.94 (w-wₗ) Qₕ pₛ/Rₛ + Wₘ s pₙ + 0.01639 C₁ L d n (P-Pₗ) N pₛ/Rₛ + Wₜ (D-Dₘ) R₂ Rₜ pₛ/Rₛ + (I + ml) pₛ/Rₛ (A)

Where

w = Weight of moisture per unit weight of bagasse.

wₗ = Maximum limit of weight of moisture per unit weight of bagasse above which furnace oil has to be used to maintain the steam pressure constant at given flow rate of steam

Qₕ = Steam flow rate (tons/hr)

pₛ = price of furnace oil (Rs/lb)

Rₛ = Steam produced per unit weight of cane (kg/kg)

Wₖ = Bagasse formation rate (tons/hr)

s = Weight of sugar (pol) per unit weight of bagasse

pₖ = Net price of sugar (Rs/kg)

C₁ = Ratio of actual steam consumption to the theoretical steam consumption.

L = Length of rollers of the mills (cm)

d = Average diameter of rollers of mills (m)

n = Angular speed of rollers of mills (rpm).
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\[ P_m = \text{Minimum value of hydraulic pressure on top Rollers of the mills (10}^3 \text{ x kg/hr)} \]

\[ N = \text{No. of mills in the tandem.} \]

\[ p_2 = \text{Price of bagasse (Rs/ton)} \]

\[ W_c = \text{Cane crushing rates (tons/hr)} \]

\[ D_m = \text{Minimum level of weight of imbibition per unit weight of cane under operational conditions.} \]

\[ R_2 = \text{Weight of exhaust steam required to evaporate unit weight of water.} \]

\[ R_3 = \text{Weight of live steam required to convert into unit weight of exhaust steam.} \]

\[ I & m = \text{constants of the linear equation for index of cane preparation.} \]

An experiment was conducted using different crushing rates to derive relationship/equations for moisture and pol in bagasse as a function of D, P and I.

Table 1: Values of Qs, Wc, Wb, I, I2 and C1 at different crushing rates

<table>
<thead>
<tr>
<th>Mills Setting (mm)</th>
<th>Crushing Rate (tcd)</th>
<th>Qs (Tons/hr)</th>
<th>Wc (Tons/hr)</th>
<th>Wb (Tons/hr)</th>
<th>I1</th>
<th>I2</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.91</td>
<td>3800</td>
<td>85</td>
<td>158.00</td>
<td>48.00</td>
<td>0.86</td>
<td>0.92</td>
<td>1.15</td>
</tr>
<tr>
<td>47.37</td>
<td>4200</td>
<td>92</td>
<td>175.00</td>
<td>53.05</td>
<td>0.86</td>
<td>0.90</td>
<td>1.30</td>
</tr>
<tr>
<td>58.30</td>
<td>5000</td>
<td>100</td>
<td>208.33</td>
<td>63.16</td>
<td>0.83</td>
<td>0.87</td>
<td>1.45</td>
</tr>
<tr>
<td>63.77</td>
<td>5400</td>
<td>106</td>
<td>225.00</td>
<td>68.21</td>
<td>0.80</td>
<td>0.85</td>
<td>1.60</td>
</tr>
</tbody>
</table>

For each crushing rate, data of moisture per unit weight of bagasse "w" and pol per unit weight of bagasse "s" at different imbibition per unit weight of cane "D", hydraulic pressure on top rollers of the mills "P" and index of cane preparation "I" was recorded. A software was used to develop linear equations for "w" and "s" in term of "I", " P" and "D". The steam flow rates (Qs) were measured for different cane crushing rates at 0.07 imbibition per unit weight of cane, 0.175 x 10^3 Kg /cm^2 hydraulic pressure on top rollers of the mills and least value of index of cane preparation (see Table 1). These values of steam flow rates were taken at 14.25 % fiber in cane and maintaining 1.0 Kg /cm^2 steam pressure at process house.

The value of "w_m" was taken as 0.49 at each crushing rate. The value of "p_1" was taken as 1.36 rupees per pound. The value of "I" was taken as 2.20. Detailed explanation may be seen in Munir (1995). The values of Wb & C1 for different crushing rates are given in Table 1. The value of "p_2" (after subtracting Excise Duty and other Levies by Government) was found to be Rs.12.00/kg. Values of "L" and "d ′" were 204 cm and 0.9652 m respectively. The experiment was conducted at 1300 rpm of turbine speed. As such, the value of "n" is taken as 4.64. The value of "P_m" was taken as 0.175 x 10^3 kg/cm^2. The value of "N" was taken as 4 as there were four mills in the tandem. The value of "p_3" was taken as Rs.500 per ton. The values of "W_c" at different mills settings, 1300 rpm of turbine speed and 14.25 fiber in cane is given in Table1. The value of "D_m" was taken as 0.07 as choking of juice gutters and tanks were observed below this limit. The value of "R_2" was taken as 0.25. One ton of exhaust steam at 120°C temperature and 1.0 Kg /cm^2 pressure is required to evaporate one ton of water in each evaporator (Eisner, 1988) and there were four evaporators in process house. The value of "R_3" was taken as 0.85.

By substituting the values of the co-efficient in the objective function, it was formed in terms of I, P, D, w and s. Then by substituting values of w and s against each crushing rate from Table 1 and by simplifying the same, the following objective function equation in term of I, P and D was established.

\[ \text{Min } Z = 61383 \times I - 27387 \times D - 309383 \times P - 309 D \]

Development of Constraint Equations

The following constraint equations were developed for the prevailing condition of Pahrianwali Sugar Mill:

1) \[ 0.1321 + 0.489 P - 0.423 D + w = 0.670 \]
2) \[ 0.07131 + 0.100 P + 0.055 D + s = 0.124 \]
3) \[ s \geq 0.0212 \]
4) \[ s \leq 0.0411 \]
5) \[ w \geq 0.4711 \]
6) \[ w \leq 0.54 \]
7) \[ X = 1 \]
8) \[ P \geq 0.175 \]
9) \[ P \leq 0.225 \]
10) \[ I \geq 0.86 \]
11) \[ I \leq 0.92 \]
12) \[ D \geq 0.07 \]
13) \[ D \leq 0.27 \]
14) \[ 41275 \times w - F = 20226 \]
15) \[ 92.82 \times I - Q_i = 74.25 \]
16) \[ 68.93 \times P - Q_2 = 12 \]
17) \[ 41.96 \times D - Q_d = 2.93 \]
18) \[ F \leq 7168 \]
19) \[ Q_1 + Q_p + Q_d \leq 43 \]

The constraint equation No.1 and No.2 at different crushing rates showed the combined effect of imbibition, hydraulic pressure and index of cane preparation on bagasse moisture and bagasse pol.
Constraint equation No.3 and constraint equation No. 4 are the lower and upper limits of pol per unit weight of bagasse respectively. The lower and upper limits of pol per unit weight of bagasse were the minimum and maximum values obtained against different crushing rates and mills settings.

Constraint equation No. 5 was the lower limit of moisture per unit weight of bagasse. The lower limit of moisture per unit weight of bagasse was the least value obtained against different crushing rates as given in Munir (1995).

Constraint equation No. 6 was the upper limit of bagasse moisture. It was observed that when moisture per unit weight of bagasse increases beyond 0.54, dumping of bagasse on the furnace grates in the form of heaps occurred due to an increase in bulk density of bagasse under the existing condition of air distribution system. The heap formation prevents the primary air supply through the dumping grates that ultimately retarded combustion due to lack of oxygen. So the upper limit for bagasse moisture was taken as 0.54.

Constraint equation No.8 was the lower limit for hydraulic pressure. Its lower limit was taken as 0.175 x 10^3 Kg/cm^2 for linear programming model.

Constraint equation No.9 was the upper limit for hydraulic pressure. It was observed that by increasing hydraulic pressure more than 0.225 x 10^3 Kg/cm^2, the temperature of outlet water of brass bearings cooling system of the rollers of the mills was found to be very high (85°C). The safe working levels of hydraulic pressure on the top rollers of the mills was taken as 0.225 x 10^3 Kg/cm^2.

Constraint equation No.10 was the lower limit of index of cane preparation. The values of lower limit of index of cane preparation (I1) are given Table 1.

Constraint equation No.11 was the upper limit of index of cane preparation. The upper limit of index of cane preparation (I2) was taken up to the temperature limit of shredder bearings (85°C). So the upper value of index of cane preparation in this safe working level is given in Table 1.

Constraint equation No.12 was the lower limit of imbibition per unit weight of cane. Its value was taken as 0.07

Constraint equation No.13 was the upper limit of imbibition. Its was observed that under the mill resource, imbibition more that 27% not only affected the cane crushing rate but also created chocking problems of mills Donnelley chutes due to slippage of bagasse at the mill. As the variation in imbibition was done at constant crushing rate in the experiment, so the upper limit of imbibition was taken as 0.27 per unit weight of cane.

Constraint equation No.14 was the quantity of furnace oil used (F) in term of bagasse moisture.

Constraint equation No 14,15,16 and 17 were the relation developed for excessive steam consumption due to increasing levels of imbibition, hydraulic pressure, index of cane preparation and imbibition at different crushing rates. The detail may be seen in Munir (1995).

Constraint equation No. 18 was a limit for furnace oil. All the four burners of boilers can spray maximum 7168.1 lbs/hr.

Constraint equation No.19 was the maximum steam generating capacity of the boiler. The maximum steam generating capacity of both the boilers was 120 tons/hr with bagasse. It was observed during the session 1994-95 that the steam generating capacity could be enhanced to 130 tons/hr by using furnace oil under the existing condition of the plant. So the excessive steam required for level of imbibition, hydraulic pressure on top rollers of the mills and index of cane preparation should be less than 130 - Qs. In mathematical form, it may be written as

\[ Q_1 + Q_2 + Q_3 \leq 130 - Q_s \]

Where \( Q_s \) is the steam consumption at imbibition 0.07 weight of water per unit weight of bagasse, 0.175 x 10^3 Kg /cm^2 of hydraulic pressure and least value of index of cane preparation (I1) as given in Table 1.

### RESULTS AND DISCUSSION

The objective function and all the constraint equations were in linear form. As such, optimization of milling performance was done using linear programming technique. A computer software “QSB” was used to solve LP model called “Quantitative System Business”. The output of LP model output of the QSB program at different crushing rate is given in Table 2.

#### Table 2. Output of LP model for different cane crushing rates

<table>
<thead>
<tr>
<th>Variable</th>
<th>Crushing Rates (tcd)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3800</td>
</tr>
<tr>
<td>X</td>
<td>1.0000</td>
</tr>
<tr>
<td>I</td>
<td>0.9200</td>
</tr>
<tr>
<td>P</td>
<td>0.2250</td>
</tr>
<tr>
<td>D</td>
<td>0.2399</td>
</tr>
<tr>
<td>S</td>
<td>0.0227</td>
</tr>
<tr>
<td>W</td>
<td>0.5400</td>
</tr>
<tr>
<td>Q1</td>
<td>11.1444</td>
</tr>
<tr>
<td>Q2</td>
<td>3.5092</td>
</tr>
<tr>
<td>Q3</td>
<td>7.1349</td>
</tr>
<tr>
<td>F</td>
<td>2140</td>
</tr>
<tr>
<td>Optimum Value (Rs/hr)</td>
<td>20500</td>
</tr>
</tbody>
</table>
The optimum value of linear programming model for different crushing rates (Table 2) indicate the minimum cost at each crushing rate for selected mill. The milling restricted the imbibition level at a point at which inefficient performance of boilers was faced due to increase in moisture. It was concluded that the present cost (Rs/hr) increased with the increase in cane crushing rates as shown in Fig. 1. The optimum values of imbibition at different crushing rates reflected that bagasse pol might be reduced even at the cost of furnace oil used in boilers as well as extra steam consumption to evaporate the additional water is mixed in evaporators under available resources of the plant. It was also noted that the value of imbibition decreased as the crushing rate increased under available resources of the plant as shown in Fig. 2. It was due to the reason that the constraint equation \( w \leq 0.54 \) resources of the plant permits maximum possible imbibition on cane for better milling results. The optimum value of hydraulic pressure at each crushing rate was found to be \( 0.225 \times 10^3 \text{ Kg/cm}^2 \). This was the maximum value of hydraulic pressure that can be set under available resources of the plant. The optimization model permitted the maximum pressure on the layer of prepared cane during operation in safe working levels to reduce the sugar and moisture in bagasse to a minimum level.
High values of index of cane preparation obtained from LP model showed that cost of pol lost in bagasse and cost of steam used due to increase in bagasse moisture were much greater as compared to the cost of steam required in increasing the level of index of cane preparation. So maximum possible disintegration of the rind of cane was suggested at milling section.

Table 3. Cost of Cane, Cost of Sugar, Total Losses, and Net Profit against different crushing Rates.

<table>
<thead>
<tr>
<th>Mills settings (mm)</th>
<th>Crushing Rate (tcd)</th>
<th>Cost of Cane (Rs/hr)</th>
<th>Cost of Sugar (Rs/hr)</th>
<th>Total Cost (L_i) (Rs/hr)</th>
<th>L* (Rs/hr)</th>
<th>L_n (Rs/hr)</th>
<th>Net Profit (P_n) (Rs/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.91</td>
<td>3800</td>
<td>95446</td>
<td>152000</td>
<td>20500</td>
<td>14968</td>
<td>5532</td>
<td>51022</td>
</tr>
<tr>
<td>47.37</td>
<td>4200</td>
<td>105493</td>
<td>168000</td>
<td>26156</td>
<td>16544</td>
<td>9612</td>
<td>52895</td>
</tr>
<tr>
<td>58.30</td>
<td>5000</td>
<td>125587</td>
<td>200000</td>
<td>35796</td>
<td>19695</td>
<td>16101</td>
<td>58312</td>
</tr>
<tr>
<td>63.77</td>
<td>5400</td>
<td>135634</td>
<td>216000</td>
<td>47061</td>
<td>21271</td>
<td>25790</td>
<td>54576</td>
</tr>
</tbody>
</table>

Economic Analysis
It was observed that as the crushing rate increased from 3800 to 5800 tons/day by increasing the mills settings, the sugar production increased but at the same time total cost (minimum value of objective function) also increased (see Table 3). The net losses (L_n) were calculated by subtracting the losses (L*) of 2.60% bagasse pol (Average figure of bagasse pol at 8.0% recovery) from the total losses “Lt” against each crushing rate. Optimum crushing capacity was calculated by subtracting the cost of sugar cane at the rate of 22.50 rupees per maund and net losses from the total sugar production at 8.00% recovery. The graph between crushing rates and net profit is shown in Fig. 3. It may be found that as the crushing rates increased, the net profit (P_n) also increased up to a crushing rate of 5000 tcd and then decreased with the increase in cane crushing rate. The crushing rate (5000 tcd) gave maximum profit and was considered the optimum crushing rate under available resources of the mill.

CONCLUSIONS
1. As the crushing rate increased from 3800 to 5400 tcd, the minimum possible milling losses also increased from 20500 to 47061 Rs/hr. under available resources of the sugar mill.
2. The optimum value of imbibition on cane decreased as the crushing rate increased under available resources of the mill.
3. The optimum value of index of cane preparation and hydraulic pressure on top rollers of the mills were found to be 0.87 and $0.225 \times 10^3 \, \text{kg/cm}^2$ respectively.
4. The optimum value of cane crushing rate was found to be 5000 tcd under existing condition of the plant which gave maximum profit of Rs. 58312/hr.

5. Results of linear programming model showed that the bagasse pol is a major milling loss that must be reduced even at the cost of other milling losses.

REFERENCES


