Optimal Logistics System for Sugarcane Mechanical Harvesting in Thailand

Jumpol Vorasayan and Supachai Pathumnakul

Abstract

Sugarcane harvesting in Thailand has steadily shifted from man to machine. This transition required changes in field preparation along with proper logistic system to improve machine productivity. We focus on improving cost of mechanical harvesting in Thailand by finding the relationship between machine productivity and row length. We, then, propose a mathematical model to optimize number of trucks per harvesters by minimizing the total harvesting cost per ton. Effects from field length, density, number of trucks, transportation cycles and in-mill operating time have been studied to find the most efficient logistic system in different scenarios.

Keywords: Logistics, Sugarcane Harvester, Optimization

Introduction

Thailand is the 2nd largest sugar exporter in the world behind Brazil. In 2010-2011 crop year, the sugarcane production hits a new record of 98 million tons (ISO, 2011). This unprecedented production quantity came from the rising trend in sugar price and popularity of using ethanol as an alternative energy (Brazil paper). On the other hand, Labor cost for manual whole stalk cutting is continually increasing. The daily minimum wage in Thailand rises 200% from approximately 150 in 1998 to 300 baht in 2013 (Thai bath : 1 THB = US $ 0.03). As a result, mechanical harvesting becomes economically feasible (Kaewtrakulpong, 2008). The amount of sugar harvested mechanically increases rapidly in recent years.

Nevertheless, mechanical harvesting efficiency in Thailand is apparently below average because of two key factors: the field length and means of transportation. Most sugarcane farming is family business hence sugarcane is cultivated in a small individual area. Mechanical harvesting in short field length incurs number nonproductive turns causing low productivity per unit time. The second problem comes from the transporters. Ten-wheel truck with 20 metric ton capacity is a common means to transport sugarcane from farms to the mill. With manual harvesting, trucks can come to pick up cane anytime during working hours. A few trucks per farm could be adequate to transport daily harvested sugarcane from a small group of workers.

In contrast, the mechanical harvester requires a transporter driving alongside to instantaneously collect chopped sugarcane. Truck must always be available otherwise harvester will become idle. In Thailand, mechanical harvesters operate during the day time while trucks commute all day and night on public network. Truck drivers prefer at least 2 rounds of daily sugarcane delivery to meet their income expectation. The proper trucks scheduling and allocations becomes critical factor.

In the last decades, there have been various studies in literature related to sugarcane harvesting mechanization around the world. In Cuba, Diaz and Perez (2000) developed simulation optimization model to maximize the total quantity of cane and minimize cycle traveling time by varying number of trucks and trailers. Milan et al. (2006) proposed MILP model to find the optimal quantity of sugarcane transported from farms to a mill by road or railway in a certain hour of a day. Grunow et al. (2007) also developed MILP model for sugarcane supply in Venezuela. Unlike in Milan et al. (2006)’s model, their variables are number of trucks on specific farm in a given day instead of sugarcane volume in a given hour. The model also includes cost from reducing crushing rate. Higgins (2006) applied a meta-heuristic transportation model to schedule vehicles picking up trailers in Australian sugar mill with the objective to minimize a combination of vehicle waiting time at the mill and mill idle time. Le Gar P-Y et al. (2008) applied a simulation software to study the various impacts occurred in sugar production from rapid increasing of mechanical harvesters in South Africa. The authors addressed that the milling period could be shorter by employing the more efficient harvesting system...
and a suitable size of transportation vehicle for various scenarios. Salassi and Barker (2008) developed a mathematical model to schedule transporting trucks in order to minimize number of trucks whose waiting times exceed specified period in Louisiana. Their model assumed the nonstop harvesting in 12.5 time frame and constant loading time of 45 minutes per truck. Results showed optimal harvesting schedule under different waiting time.

In this paper, we study the logistic system of mechanize harvesting to demonstrate how much cost per ton can be achieved by changing field length and number of transporters. The proposed optimization model determines the suitable number of trucks per harvester and the number of transport cycles per truck in order to minimize the total harvesting cost for a specific field length. The obtained results could assist sugar mill and farmer to understand the benefit of proper redesigned systems and it could be applied to improve sugar cane logistics efficiency and lesson cost per ton of mechanical harvesting in Thailand.

Experimentation:
1. Sugarcane mechanical harvester cost model:
   In the section, the cost model is developed. It is based on some following assumptions:
   1. Harvesters and transporters are bought new and resale after 10 years.
   2. Transporters are 6 to 18 wheel trucks whose capacities range from 5 to 40 tons which are most common transporters in North-Eastern region of Thailand.
   3. Every transporter should operate with the same number of transporting trips, driving from the farm to the mill and back to the farm daily.
   4. At beginning of the day, all transporters are available in field and cutting continues until the last transporter has been filled.
   5. The waiting time in the mill is independent of number of trucks per harvester.

The notations for the proposed cost model are as follows:

\[ f \quad \text{Field length (meter) (variables)} \]
\[ d \quad \text{Distance between farms and mills (kilometer)} \]
\[ y \quad \text{Sugar yield (ton/rai) (noted that one Thai rai = 0.4 ha)} \]
\[ r \quad \text{Row width (meter)} \]
\[ t_o \quad \text{In-mill operating time (i.e., checking in, weighting, waiting, unloading) (hour)} \]
\[ n_t \quad \text{Number of transporters per harvester} \]
\[ r_t \quad \text{Number of transporter trip} \]
\[ f_c \quad \text{Fuel cost} \]
\[ i \quad \text{Interest rate} \]

For harvesters,
\[ p_h \quad \text{Price of brand new harvester (unit cost)} \]
\[ w_{hf} \quad \text{Fixed wage for a harvester driver (unit cost/day)} \]
\[ w_{hv} \quad \text{Variable wage for a harvester driver (unit cost/ton)} \]
\[ l_h \quad \text{Period of use of a harvester (year)} \]
\[ s_{vh} \quad \text{Resale value of a harvester (unit cost)} \]
\[ m_h \quad \text{Maintenance cost of harvester (unit cost/ton)} \]
\[ s_h \quad \text{Average harvester speed when cutting straight (kilometer)} \]
\[ w_{oh} \quad \text{Harvester working hour (hour/day)} \]
\[ d_{ah} \quad \text{Number of working days in a crop year (day)} \]
\[ g_h \quad \text{Fuel consumption rate of a harvester (liter/hour)} \]

For Transporters
\[ p_t \quad \text{Price of a brand new transporter (unit cost)} \]
\[ w_{tf} \quad \text{Fixed wage for a transporter driver (unit cost/day)} \]
\[ w_{tv} \quad \text{Variable wage for a transporter driver (unit cost/ton)} \]
\[ l_t \quad \text{Period of use of a transporter (year)} \]
\[ s_{vt} \quad \text{Resale price after use (unit cost)} \]
\[ c_t \quad \text{The capacity of transporter (ton)} \]
\[ t_f \quad \text{In-field transporting time (minute)} \]
\[ t_r \quad \text{In-field transport transition time (minute)} \]
\[ s_t \quad \text{Highway transporter average speed (kilometer/hour)} \]
\[ g_{tr} \quad \text{Highway transporter fuel consumption (kilometer/liter)} \]
\[ g_{tf} \quad \text{In-field transporter fuel consumption (kilometer/liter)} \]

The model is formulated as follows:
Time for 1 cycle of transport \((t_c, \text{ minute})\),

\[
t_c = t_f + t_i + \frac{d}{s_t} \cdot 60 + 2 + t_q \cdot 60
\]

where the formula for the loading time per 20 tons \((t_l)\) is

\[
t_l = \frac{60 \times c_t}{v_h \times \frac{y}{1600} \times 1000 \times \frac{b(f)}{100}}
\]

With data collected from participated company in the crop year 2011/2012, the average values of the model parameters as shown in Table 1 are used in this study. The costs of a harvester and truck are presented in the Table 2.

### Table 1: Model parameters of the case study mill in the crop year 2011/2012.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average values</th>
<th>Parameter</th>
<th>Average values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_c)</td>
<td>35 THB*/liter</td>
<td>(p_c)</td>
<td>1 x 10^7 THB</td>
</tr>
<tr>
<td>(i)</td>
<td>5%</td>
<td>(w_{ct})</td>
<td>250 THB/day</td>
</tr>
<tr>
<td>(p_h)</td>
<td>12 x 10^6 THB</td>
<td>(w_{ct})</td>
<td>5 THB/ton</td>
</tr>
<tr>
<td>(w^{roll})</td>
<td>340 THB/day</td>
<td>(l_t)</td>
<td>10 years</td>
</tr>
<tr>
<td>(w_{bc})</td>
<td>5 THB/ton</td>
<td>(s_{v_t})</td>
<td>3 x 10^6 THB</td>
</tr>
<tr>
<td>(t_{bc})</td>
<td>10 years</td>
<td>(c_t)</td>
<td>20 tons</td>
</tr>
<tr>
<td>(w_{bck})</td>
<td>5 x 10^6 THB</td>
<td>(t_f)</td>
<td>15 min.</td>
</tr>
<tr>
<td>(m_{sh})</td>
<td>19.33 THB/ton</td>
<td>(t_f)</td>
<td>3 min.</td>
</tr>
<tr>
<td>(s_h)</td>
<td>5 km/hr.</td>
<td>(s_{v})</td>
<td>50 km./hr.</td>
</tr>
<tr>
<td>(w_{oa})</td>
<td>12 hr./day</td>
<td>(g_{sr})</td>
<td>3 km./liter</td>
</tr>
<tr>
<td>(d_h)</td>
<td>100 days</td>
<td>(g_{sl})</td>
<td>2 km./liter</td>
</tr>
<tr>
<td>(g_{sh})</td>
<td>55 liter/working hour</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Thai bath : 1 THB = US $ 0.03.

### Table 2: Cost equations for sugarcane harvester and transporter.

<table>
<thead>
<tr>
<th>Cost (THB per ton)</th>
<th>Harvester</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel ((t_f + t_q)\frac{r_x \times r_x \times g_h \times f_c}{60\alpha})</td>
<td>(\frac{2 \times r_x \times d \times f_c}{g_{sr}})</td>
<td>(+ \frac{c_f \times f_c}{g_{stf} \times 1600 \times 1000}) (/\alpha)</td>
</tr>
<tr>
<td>Consumable material ((obtained))</td>
<td>12.86</td>
<td>7.84</td>
</tr>
<tr>
<td>Maintenance ((obtained))</td>
<td>19.33</td>
<td>28.13</td>
</tr>
</tbody>
</table>
| Depreciation \(p_h \frac{[(1+i)^n-1]}{(1+i)^n-1} - SV_h \frac{i}{(1+i)^n} - pr \frac{[(1+i)^l-1]}{(1+i)^l-1} - SVr \frac{i}{(1+i)^l} - \)
| Labor + Motivation \(\frac{w_h \alpha}{\alpha}\) | \(w_{r} \alpha\) |
| Administrative Insurance and others \(\frac{180,000}{d_h \alpha}\) | \(70,000\) | \(\frac{16,000}{d_h \alpha}\) | \(78,000\) |
With \((n_t, t)\) as variables, the optimization model for minimizing cost is

\[
\text{Min Total Harvester Cost} + \text{Total Transporter Cost}
\]

Subject to

\[
1 \leq n_t \leq \frac{w_h}{\left(\left(t_1 + t_2\right)/60\right)} \quad (6)
\]

\[
1 \leq t_1 \leq \frac{w_h}{t_c} \quad \text{If } w_h = 60 - \frac{w_a}{t_c} \times t_c + t_f + t_l < 0 \quad (7)
\]

\[
1 \leq t_1 \leq \frac{w_h}{t_c} + 1 \quad \text{If } w_h = 60 - \frac{w_a}{t_c} \times t_c + t_f + t_l \geq 0 \quad (8)
\]

RESULT AND DISCUSSION

3.1 Utilization of Harvester vs Field Length:

The first key factor is the field length. Unlike Australia, Brazil and USA, Thai farmers still grow their crops in their separated private fields which are relatively small and short length. This causes harvester to perform less efficiently because it needs roughly 2 minutes of turning time when it reaches the end of the field. We conducted time studies of mechanical harvesting on 16 different field locations in the north-eastern part of Thailand. Out of all activities, the only productive activity of sugarcane harvester is cutting cane \((t^1)\). The other activities that occur while the machine is running \((t^2)\) are considered wastes. To focus our attention on only field length, we exclude activities that are independent of field length such as turn away from obstacles, waiting for a next trucks etc. Therefore, \(t^2\) is just the turning time at the end of field and utility of harvester is simply

\[
\text{Utilization} = \frac{20\times 100}{t_1 \times 100} \quad (9)
\]

We perform an experiment of 38 samples from 13 sugarcane fields with the length of 60, 65, 100, 140, 200, 205, 246, 250, 300, 301, 320, 340, 650 meters. The relationship of utilization to field length is depicted in figure 1. The solid line is a utilization function with the least mean absolute percentage errors (MAPE = 26.87\%). \(p(f) = 15.209\ln(f) - 18.988\). The utilization function can also be obtained by computing the distance for filling 20 tons of sugarcane in the trucks from this formula, \(20\frac{y}{t_1} \times 1000\) km. Then let a number of turns equals to the distance divided by field length. However, it could have some errors from uneven speed from acceleration and deceleration after and before turning.

Fig. 1: Field Length vs. Utilization.

3.2 Field length and density:

We experiment the individual effect of 4 key factors i.e. field length and density. Cost can be found by the mathematical model with utility function obtained in the previous section. Values of variables except the experimented factors are set as follows \(f = 250, y = 12, d = 30, t_2 = 2, n_t = 4\) and \(r_1 = 2\).

Results in figures 2 and 3 show that increasing both field length and density will lower harvesting costs. For field length shorter than 300 meters, additional length of 100 meters can improve truck utilization by 5 to 15%. The improvement diminishes as the longer field length. Total cost versus density exhibits similar trend but the relationship is more linear. If the current density is less than 16 ton/rai, increasing density by 2 ton/rai would improve cost from 1% to 5%.
3.3 In-mill operating time:

The in-mill operating time \( t_q \) consists of 3 main activities; waiting, weighting, and unloading. Weighting and unloading times are rather constant while the waiting time is varied by number of trucks in the mill, the variability of truck arrival time and sugarcane crushing time. During peak period, milling process becomes the bottleneck for the whole system, \( t_q \) can be unexpectedly long and then leads to minimal number of transportation cycles. The relationship between \( t_q \) and \( n_t \) is obviously significant but it is beyond our scope of this research. Nevertheless, we experiment the total cost with different \( t_q, n_t \) and \( r_t \) as presented in table 3.

Table 3: Total costs incurred by different number of trucks and its maximum number of cycles for different in-mill operating times at \( f = 250, y = 12, d = 30 \).

<table>
<thead>
<tr>
<th>( t_q )</th>
<th>( n_t )</th>
<th>( r_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>16</td>
</tr>
</tbody>
</table>

At specified number of trucks, the higher number of transportation cycles lower the total cost per ton since the benefit from harvesting quantity outweighs the extra fuel and labor costs. So optimal total cost for each \( n_t \) comes with its maximum \( r_t \). The longer in-mill operating time means lower number of possible transporting cycles thus higher cost. This is significant at low number of trucks where multiple transporting cycles can be achieved. For example, at \( n_t = 3 \), the maximum \( r_t \) drops from 4 to 1 by rising \( t_q \) from 1 to 8 and the corresponding total cost considerably changes from 254 to 504 baht per ton. We can notice that the optimal combination of \( (n_t, r_t) \) for particular \( t_q \) is varied. At \( t_q = 1 \), \( (n_t = 5, r_t = 4) \) yields the lowest cost than \( (n_t = 6, r_t = 3) \),
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\( (n_t=10, r_t=2) \) and \( (n_t=15, r_t=1) \). Nonetheless, at \( tq = 3 \), the most economical \( (n_t,r_t) \) is \( (n_t=10, r_t=2) \). Then at \( t_q = 8 \), it is cheaper to have 15 trucks with one cycle each. The next section has more details about \( (n_t,r_t) \).

3.4 Optimal Number of trucks and transportation cycles:

Variables of the optimization model are number of trucks \( (n_t) \) and transportation cycles \( (r_t) \) while constrains are their corresponded minimum and maximum values. The upper bound of one variable is a function of the other. Therefore, variables are mutually dependent. Increasing a number of trucks will lower a number of times all assigned trucks can finish transporting in one day. Likewise, as stated in assumption 3, increasing number of transportation cycles will lower the maximum number of trucks that can finish the specified number of cycles in one day. The maximum \( n_t \) and the maximum \( r_t \) can be improved by increasing field length and density so that each cycle takes shorter time. The example can be found in figure 4 and 5.

Fig. 4: The minimum field length that certain \( (n_t,r_t) \) can be achieved at \( y = 12, d = 30, t_q = 2 \).

Fig. 5: The minimum density that certain \( (n_t,r_t) \) can be achieved at \( f = 250, d = 30, t_q = 2 \).

Figure 4 shows field length that the specific \( (n_t,r_t) \) can be achieved. For example, at \( (n_t,r_t) = (8,1) \), the field length must be at least 50 meters. Then, if at \( (n_t,r_t) = (8,2) \), the field length cannot be less than 100 m. And at \( (n_t,r_t) = (8,3) \), the field length has to be at least 1000 m. Figure 5 shows similar but rather linear and lower slope effect. At \( (n_t,r_t) = (8,1) \), density of 6 ton/rai is enough but if \( (n_t,r_t) = (8,2) \), it requires density at least 10 ton/rai. For \( (n_t,r_t) = (8,2) \), density must not be less than 16 ton/rai. Note that at \( (n_t,r_t) = (15,3) \) can be achieved at density 32 ton/rai in 250m long field while at density 12 ton/rai, \( (n_t,r_t) = (15,3) \) is not possible regardless of the field length.

The Tables 4-6 show the optimal \( (n_t,r_t) \), their corresponding minimum total cost at specific field length and density with various distance and in-mill operating time. In line with results from previous section, total costs could be improved by increasing both variables. But the improvement level subsides at higher field length and density. Comparing the 4th row in the Table 4 to cost in figure 2 where \( y = 12, d = 30, t_q = 2, n_t = 4 \) and \( r_t = 2 \), we can gain from 15% to 27% in cost reduction by applying optimal \( (n_t,r_t) \).
Table 4: The optimal \((n_t,r_t)\) and its corresponding total cost at \(d = 30, t_s = 2\).

<table>
<thead>
<tr>
<th>Field length [m]</th>
<th>Density/ton/m²</th>
<th>Total cost [THB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>200 (15.0)</td>
<td>211 (19.2)</td>
</tr>
<tr>
<td>200</td>
<td>192 (17.2)</td>
<td>207 (20.2)</td>
</tr>
<tr>
<td>300</td>
<td>185 (19.2)</td>
<td>200 (21.2)</td>
</tr>
<tr>
<td>400</td>
<td>183 (19.2)</td>
<td>201 (21.2)</td>
</tr>
<tr>
<td>500</td>
<td>182 (19.2)</td>
<td>198 (21.2)</td>
</tr>
<tr>
<td>600</td>
<td>181 (19.2)</td>
<td>195 (21.2)</td>
</tr>
<tr>
<td>700</td>
<td>180 (19.2)</td>
<td>193 (21.2)</td>
</tr>
<tr>
<td>800</td>
<td>178 (19.2)</td>
<td>190 (21.2)</td>
</tr>
</tbody>
</table>

Table 5: The optimal \((n_t,r_t)\) and its corresponding total cost at \(d = 30, t_s = 4\).

<table>
<thead>
<tr>
<th>Field length [m]</th>
<th>Density/ton/m²</th>
<th>Total cost [THB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>211 (15.2)</td>
<td>255 (19.2)</td>
</tr>
<tr>
<td>200</td>
<td>202 (17.2)</td>
<td>250 (20.2)</td>
</tr>
<tr>
<td>300</td>
<td>197 (19.2)</td>
<td>247 (21.2)</td>
</tr>
<tr>
<td>400</td>
<td>199 (20.2)</td>
<td>246 (22.2)</td>
</tr>
<tr>
<td>500</td>
<td>195 (21.2)</td>
<td>245 (22.2)</td>
</tr>
<tr>
<td>600</td>
<td>193 (21.2)</td>
<td>241 (22.2)</td>
</tr>
<tr>
<td>700</td>
<td>192 (21.2)</td>
<td>238 (22.2)</td>
</tr>
<tr>
<td>800</td>
<td>190 (21.2)</td>
<td>235 (22.2)</td>
</tr>
</tbody>
</table>

Table 6: The optimal \((n_t,r_t)\) and its corresponding total cost at \(d = 60, t_s = 2\).

<table>
<thead>
<tr>
<th>Field length [m]</th>
<th>Density/ton/m²</th>
<th>Total cost [THB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>246 (15.2)</td>
<td>352 (15.2)</td>
</tr>
<tr>
<td>200</td>
<td>237 (17.2)</td>
<td>350 (19.2)</td>
</tr>
<tr>
<td>300</td>
<td>232 (19.2)</td>
<td>246 (21.2)</td>
</tr>
<tr>
<td>400</td>
<td>239 (20.2)</td>
<td>227 (21.2)</td>
</tr>
<tr>
<td>500</td>
<td>228 (21.2)</td>
<td>225 (22.2)</td>
</tr>
<tr>
<td>600</td>
<td>225 (22.2)</td>
<td>225 (22.2)</td>
</tr>
<tr>
<td>700</td>
<td>222 (22.2)</td>
<td>222 (22.2)</td>
</tr>
<tr>
<td>800</td>
<td>222 (22.2)</td>
<td>222 (22.2)</td>
</tr>
</tbody>
</table>

The higher in-mill operating time and higher distance between farm to mill, decrease the maximum \(n_t\) and \(r_t\), resulting in higher cost. With 2 hours longer in-mill operating time, the average additional cost from table 3 to 4 is 12 baht. For 30 meters more distance, the average additional cost from table 4 to 6 is 43 THB.

**Conclusion:**

This research is conducted to improve utilization of mechanical harvester and lower overall sugarcane harvesting cost in Thailand. To reduce total cost, field length, density must be higher and the in-mill operating time must be lower. The cost saving per unit is higher at shorter field or lower density. The effect is slighter at the longer field length or higher density.

Harvesters need transporters to carry chopped cane while it is operating. Ideally, harvester can operate continuously if transporters are always present. However, during peak period, all trucks are busy carrying goods on the road or waiting to unload. Insufficient number of trucks and few transportation cycles reduce harvester working time. These two factors must be considered together since one factor limits the maximum possible value of the other and vice versa. The maximum \(n_t\) and \(r_t\) also change with parameters. Different scenarios require different values of \((n_t,r_t)\) to minimize total costs.

**REFERENCES**


