A SIMULATION MODEL OF A SUGAR CANE SUPPLY SYSTEM

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ABSTRACT

The loading and transportation system used by the cooperative farms to deliver cane to the Frome Sugar Factory was analyzed and digital computer simulation model constructed to reflect the operational characteristics of the system. The activity times of the field equipment were represented by GAMMA distributions in the model, while normal distributions were used for the road speeds of transport units. The data used to estimate the parameters of the distributions were collected by conducting time and motion studies of the operations. The results of operating the model showed very close association (\( > 80\% \)) between observed and simulated data.

The model was used to predict the potential output of systems with various combinations of wagons, infield tractors, road haulage tractors and 1 loader. The results of these simulations showed that the current policy of restricting the daily quota allotted to each farm to 320 tons led to under-utilization of the equipment for most travel distances. Rental and owning costs considerations were used to identify: (1) systems with the lowest total cost for various travel distances, and (2) the distance at which various combinations become cheaper to operate.

Other results indicated that transport units travelling for distances greater than 5 miles to the factory should be given priority at the factory yard, and that adding a second infield tractor to systems with only one, only marginally increased the potential output under the conditions studied.

INTRODUCTION

Background

Sugar cane harvesting and transportation involves a series of operations...
which include: cutting, loading, transportation to factory or transfer station, weighing, unloading, taring and travel back to the field. The overall efficiency of such a series of operations depends on the efficiency of each individual operation (Boyce and Phillips\textsuperscript{1}).

In the Jamaican context, the harvesting and transportation system for sugar cane has been considered as one of the main factors reducing the overall production efficiency of the sugar industry (Chinloy\textsuperscript{4}), based on the following indicators:

1. Factory lost time due to "out-of-cane".
2. Stale cane delivered to factories for processing.

However, since sugar production is a complex operation which includes many variables ranging from weather conditions to quality of personnel employed, it is difficult to ascertain to what extent field operations in harvesting contribute to the overall lowering of production efficiency.

Literature Review

Economic Loss

Between cutting and milling, stalks of sugar cane undergo a progressive deterioration (staling and souring) characterized by loss of moisture and sucrose and an accumulation of reducing sugars, organic acids and polysaccharides, mainly dextrans (Tilbury\textsuperscript{12}). This rate of deterioration increases with the increased time lapse, leading to significant economic loss (Chinloy\textsuperscript{4}). After much study of the mechanism and organisms involved, Tilbury\textsuperscript{15} concluded that the only feasible method of reducing these losses was to minimize the delay between harvest and milling. In an earlier publication, Tilbury\textsuperscript{14} had suggested that the problem of staling in the Jamaican context was primarily one of logistics.

Besides the economic loss sustained due to the deterioration of cane quality, further losses are encountered from under-utilization of factory machinery and the extension of the crop harvest period. Nurse\textsuperscript{7} showed that during the period 1969 to 1973 an average of 39\% of total available time was lost for various reasons, including almost 10\% due to field stoppages which resulted in factories being out-of-cane. Chinloy\textsuperscript{4} demonstrated that the overall effect of factory stoppages, which forced an extension of the crop harvest period, further reduced the average quality of cane ground.

Symbolic and Mathematical Models

Tomlinson\textsuperscript{16}, in an assessment of the ills of the Caribbean sugar industry, highlighted the need for greater efficiency in organizing and planning the use of harvesting equipment and proposed that the techniques of operations research (OR) could be found useful in this development.

In general, the application of OR techniques requires the construction
of a model which incorporates all the important characteristics of the system. Boyce\(^2\) classifies 3 types of models: iconic, analog and symbolic. Iconic models look like the subject of inquiry and are characterized by some scaling effect; Analog models are characterized by the use of a convenient transformation of one set of properties for another; and symbolic models are characterized by the representation of system by mathematical or logical symbols. Symbolic models are of a particular interest here.

Most harvesting systems can be represented by the symbolic model, as illustrated in Fig. 1 and can be generally grouped as closed circuit transport systems (Boyce\(^3\)). In general, this model can be broken into 2 separate subsystems; one located at the field and the other at the installation (factory, mill, dryer or other). Each subsystem can be represented by a queuing model in which transport units queue at the field and factory awaiting service. The length of time each arriving customer must wait in line (queue) for service depends on the number of other customers in the queue, the service rate and the rate of arrival at the queue (Saaty\(^1\)). The successful use of mathematical models to represent real queuing systems depends primarily on the identification of the form of the probability distributions which best represent the arrival and service rate distributions (Page\(^9\), Phillips\(^9\), Hillier and Lieberman\(^6\)).

![Figure 1](image-url)
Various methods exist to determine the correct form of the probability distributions. Several of these were calculated by Dumont and Boyce for agricultural unit operations. The so called GAMMA distribution was identified as the more general one and appropriate for a number of operations.

Simulation

Simulation is one of the most widely used and accepted tools of system analysis and is defined as: A numerical technique for conducting experiments on a digital computer which involves certain types of mathematical and logical relationships necessary to describe the behavior and structure of a complex real world system over extended periods of time (Phillips et al.). This versatile technique is, however, imprecise and provides only statistical estimates rather than exact results.

This approach was, however, selected for use in the study of the harvest and transport system at Frome based on the advantages it offered while in full cognizance of its limitations. The model was constructed using the so called GASP IV simulation method (Fig. 2) as developed by Pritsker and presented in his book “The GASP IV Simulation Language”.

Objectives

The aim of this work was to study one sugar cane harvesting and handling system used by the Frome Co-operatives and to:

1. determine the current level of utilization of the various equipment within the system and the overall output of the system;
2. construct a simulation model which reflects the operational characteristics of the system studied;
3. use the simulation model to determine the effect on potential output of the system due to variations in the characteristics or specifications of different components in the system; and
4. use the simulation model to test recommendations which may be implemented to optimize system performance.

MATERIALS AND METHODS

To predict the effect of various practices governing the selection of cane cutting areas, and the allocation of harvesting and transportation equipment, a workable and reliable analytical description of the system was needed. Symbolic mathematical models were used to describe the various pieces of equipment and to show how such equipment is influenced by environmental conditions. A computer simulation model of the system was constructed and used to predict the effect of various changes within the system.
FIGURE 2. Functional flow chart of a GASP IV program (adapted from Pritsker, 1974).
In this analysis, a system was considered as being composed of a number of interrelated parts of subsystems, all of which have a common purpose (Boyce). In particular, the system studied was composed of all the operations and equipment used after the cane had been cut, until it was finished being unloaded at the factory. General information about the system was collected from the co-operative farms supplying the Frome Sugar Factory. Time study data were collected from Farms 1 and 3 to construct statistical models of the operating times of the loader, the infield tractor and the road haulage tractor. Figs. 3 and 4 show generally the flow system considering the movement of wagons.

FIGURE 3. Field operations — wagons being loaded.
WAGON WAITS TO BE LOADED
WAGON IS MOVED TO LOADER
WAGON IS LOADED
WAGON IS MOVED AWAY FROM LOADER
WAGON WAITS TO BE MOVED TO FACTORY
WAGON TRAIN IS MOVED TO FACTORY
WAGON TRAIN WAITS TO BE WEIGHED
EACH WAGON IS WEIGHED SEPARATELY
WAGON TRAIN IS MOVED TO UNLOADER
WAGON WAITS TO BE UNLOADED
EACH WAGON IS UNLOADED SEPARATELY
WAGON TRAIN IS MOVED TO SCALES
WAGONS WAIT TO BE WEIGHED
EACH WAGON IS WEIGHED SEPARATELY
WAGON TRAIN IS RETURNED TO FIELD

**Figure 4.** Flow process chart of activities performed on each wagon.
RESULTS AND DISCUSSION

Data Analysis

During the analysis of the data some values were deleted where:

1. the remarks recorded by the recording personnel indicated irregularities (e.g. unscheduled breaks resulting in extended activity times, of extended loading and/or travel times when 2 or more wagons were pulled into the field for loading) or

2. the fitted distributions showed the skewing effect of extreme values.

As a result, it may be inferred that:

1. the systems studied showed some characteristics of a system operating in an unsteady state, and

2. the assumption that the data fit GAMMA distributions should be re-examined. Notwithstanding these restrictions, the parameters calculated for the various distributions were used to test the simulation model.

Input Data and Initial Tests of the Simulation Model

The operation of the simulation model was tested by entering as data the parameters of the statistical distributions representing the equipment and operating conditions (Table 1). Initial runs were made varying the random number of seeds used in generating random deviates from the various distributions. Comparisons of the output of these runs showed that the variation in the quantities measured was less than 1%. One set of random numbers was therefore chosen and used throughout the simulation analysis. Histogram plots of the predicted process times were also examined to ensure that there was no bias in the numbers generated.

The equipment combinations operated on Co-op Farms 1 and 3 were simulated delivering a daily quota of 1,000 tons and the program set up to simulate 10 consecutive days (20 shifts) of operations.

Model Verification

In order to verify the model, the equipment combinations operating on Farm 1 and Farm 3, conditions were simulated for distances of 6.1 and 4.5 miles to the factory, respectively. The inter-arrival times of the road haulage tractors from each farm at the factory were calculated by taking the difference between the times of successive arrivals for both observed and simulated data; arrivals after the end of each shift were ignored. The Mann-Whitney U test (Siegel12) was then used to test the hypothesis that the observed and simulated inter-arrival times have the same distribution. The test showed that in both
cases (Farms 1 and 3) there was a 90% chance that the observed and simulated data have the same distribution. The observed inter-arrival times were collected during the same time period as the data used to estimate the parameters of the distributions used in the simulation.

**TABLE 1.** Input data for the statistical distributions representing the various activity times

<table>
<thead>
<tr>
<th>Activity Type of distribution</th>
<th>Input data, Farm 1</th>
<th>Input data, Farm 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTPW - loading time per wagon</td>
<td>Gamma</td>
<td>A</td>
</tr>
<tr>
<td>TSFT - travel speed to factory</td>
<td>Normal</td>
<td>Minimum</td>
</tr>
<tr>
<td>RTFT - residence time in factory yard</td>
<td>Gamma</td>
<td>A</td>
</tr>
<tr>
<td>TSFD - travel speed to field</td>
<td>Normal</td>
<td>Minimum</td>
</tr>
<tr>
<td>TTLD - travel time to loader</td>
<td>Erlang</td>
<td>A</td>
</tr>
<tr>
<td>TTFD - travel time to factory</td>
<td>Erlang</td>
<td>Minimum</td>
</tr>
<tr>
<td>TTLD - travel time to loader</td>
<td>Erlang</td>
<td>A</td>
</tr>
<tr>
<td>RTFT - residence time in factory yard</td>
<td>Erlang</td>
<td>Minimum</td>
</tr>
<tr>
<td>LI - loader idle time</td>
<td>Erlang</td>
<td>A</td>
</tr>
<tr>
<td>MIN - minimum values associated with parameter sets 1-7</td>
<td>Erlang</td>
<td>Minimum</td>
</tr>
</tbody>
</table>

1scale factor for Gamma and Erlang distributions; mean for normal distributions
2shape factor for Gamma and Erlang distributions; standard deviation for normal distributions

This statistical verification was augmented by comparing observed and simulated values of system performance indicators (Table 2).

**Some Results from the Simulation Analyses**

The indication from Figs. 5, 6, 7 and 8 are:

1. **Under Farm 3 conditions,** all equipment combinations supply 10 to 20% more cane than under Farm 1 conditions. This results from a higher mean travel speed of the road haulage tractor and the more stable operation of the loader on Farm 3.

2. **In single road haulage tractor systems,** the maximum output is limited by the road haulage tractor for all distances and any number of wagons greater than 8. (Observe the cluster of the lines in Fig. 5).

3. **In systems using 2 road haulage tractors,** the maximum output is restricted by distance and the number of wagons up to 14 (Fig. 5). When 14 or more wagons are used, the infield tractor limits the
maximum output up to 5 miles and for greater distances, the utilization of the road haulage tractors approaches 100% and the output decreases with increasing distance.

### TABLE 2. System performance indicators (observed and simulated compared)

<table>
<thead>
<tr>
<th></th>
<th>Farm 1</th>
<th>Farm 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Simulated</td>
</tr>
<tr>
<td>Work period (hours)</td>
<td>7.25*</td>
<td>8.00</td>
</tr>
<tr>
<td>Distance to factory (miles)</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>No. of trips completed per shift</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Average total trip time (hours)</td>
<td>1.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Utilization factors:
- Loader: 0.82, 0.91, 0.59, 0.54
- Infield tractor: 0.93, 1.00, 0.80, 0.52
- Road haulage tractor (1): 0.75, 0.89, 0.95, 0.99
- Road haulage tractor (2): 0.66, 0.88, -, -

1. Average of two consecutive shifts (77.01.18)
2. Average for 20 consecutive shifts
3. One trip equivalent to 40 tons
4. *1.5 hour lost at the start of the second shift when the loader ran out of fuel

In practical terms, the indications are that some improvement in the overall output of the system can be attained by improving the field operations by:

1. Reorganizing the quota allocations so that the full potential of the existing fleet of equipment can be realized. The indications are that the present fleet could supply the full daily quota (2,000-3,000 tons) allotted to the Co-ops without the assistance of private contractors. This, however, will require much improvement in:
   - (a) the maintenance system (as the assumption was made that there was no lost time due to breakdowns), and
   - (b) the approach of the operators.

2. Reducing the variability of the loading time per wagon;

3. Controlling the placement of the wagons, thereby reducing the variation of the travel time of the infield tractor to and from the loader; and

4. Operating 2 road haulage tractors along with more than 8 wagons for travel distances greater than 1 mile to the factory.

The results further indicate that the practices at Frome of operating
FIGURE 5. Simulated output vs. travel distance to factory.

FIGURE 6. Comparison between restricted and open quota policies (output and equipment rental cost vs. travel distance to factory).
2-shifts which deliver only 320 tons each day (160 tons/shift) under-utilizes the equipment resulting in a very high cost of loading and transport. Figure 6 shows the effect of this quota arrangement under the present policy of charging out equipment at a fixed hourly rate. Note that the expected saving is between $1.00 and $1.20 per ton when the same charge-out rates are applied to the simulated output.

Using the simulated output figures and an assumed cost structure (Table 3), the results of changing combinations of equipment can be calculated. Figure 7 shows that effect. These figures include all owning and operating costs.

**TABLE 3. Owning and operating cost structure assumed**

<table>
<thead>
<tr>
<th>Machine specifications</th>
<th>Loader</th>
<th>Infield tractor</th>
<th>Road haulage tractor</th>
<th>Wagon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity (ton/hour)</td>
<td>60</td>
<td>70 (crawler)</td>
<td>83 (standard)</td>
<td>10</td>
</tr>
<tr>
<td>Fuel consumption (gal/hour)</td>
<td>2.66</td>
<td>2.98</td>
<td>2.96</td>
<td>-</td>
</tr>
<tr>
<td>Length of cropping season (175 days @ 16 hours per day) (hours)</td>
<td>2800</td>
<td>2700</td>
<td>2800</td>
<td>2800</td>
</tr>
<tr>
<td>Life in years (cropping seasons)</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Initial cost ($Ja)*</td>
<td>30000</td>
<td>40000</td>
<td>15000</td>
<td>10000</td>
</tr>
</tbody>
</table>

**Average fixed costs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Loader</th>
<th>Infield tractor</th>
<th>Road haulage tractor</th>
<th>Wagon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation (straight line, no resale value) ($Ja)</td>
<td>6000</td>
<td>5714</td>
<td>3000</td>
<td>1000</td>
</tr>
<tr>
<td>Interest + insurance + housing @ 20% p.a. S.I. on 1/4 initial cost ($Ja)</td>
<td>3000</td>
<td>4000</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Total annual fixed cost ($Ja)</td>
<td>9000</td>
<td>9714</td>
<td>4500</td>
<td>2000</td>
</tr>
<tr>
<td>Total fixed cost ($Ja/hour)</td>
<td>3.21</td>
<td>3.47</td>
<td>1.61</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Average operating cost**

<table>
<thead>
<tr>
<th>Description</th>
<th>Loader</th>
<th>Infield tractor</th>
<th>Road haulage tractor</th>
<th>Wagon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repairs (100% initial cost over life) ($Ja/hr)</td>
<td>2.14</td>
<td>2.04</td>
<td>1.07</td>
<td>0.36</td>
</tr>
<tr>
<td>Fuel (@ $Ja 1 per gal.) ($Ja/hour)</td>
<td>2.65</td>
<td>2.98</td>
<td>2.96</td>
<td>-</td>
</tr>
<tr>
<td>Total operating cost ($Ja/hour)</td>
<td>4.80</td>
<td>5.02</td>
<td>4.03</td>
<td>0.36</td>
</tr>
</tbody>
</table>

* $Ja – Jamaican dollar. ($Ja 1 = $Can 1)

Residence time in the factory yard is also implicated in output reduction. Figure 8 shows that effect for both Farms 1 and 3 when a system with 12 wagons, 1-loader, 1-infield tractor and 2-road tractors is used.
FIGURE 7a. Equipment owning and operating costs and simulated output vs. travel distance to factory for various equipment combinations.
FIGURE 7b. Equipment owning and operating costs and simulated output vs. travel distance to factory for various equipment combinations.
FIGURE 8. Residence time in factory yard (RT) vs. simulated output vs. various travel distances to the factory for a 12-112 system.
CONCLUSIONS

(1) The approach adopted is a good method of analyzing cane harvesting system.

(2) The simulation model gives a good representation of the system used by the Co-ops to deliver cane to the Frome Factory.

(3) Equipment combinations which represent the least cost systems for various travel distances have been identified.

(4) The limiting effect on systems output of increasing residence time in the factory yard has been demonstrated.

(5) GASP IV Simulation Language was found to be a very useful tool in constructing the simulation model of the cane harvesting systems.

REFERENCES


UN MODELO SIMULANDO EL SISTEMA DE SURTIR DE LA CAÑA DE AZUCAR

C. O. Lee

RESUMEN

Los sistemas de carga y transportación usadas por las granjas cooperativas para transmitir caña a la Frome Sugar Factory fue analizada y una computadora digital de modelo de simulación fue construida para reflejar las características de operación del sistema. Las horas de actividad del equipo de campo, fueron representadas por distribuciones GAMMA en el modelo, mientras distribuciones normal se usaron para velocidades de carretera de las unidades de transporte. Los datos solían calcular los parámetros de la operación. Los resultados de la operación del modelo mostraron una asociación muy cercana (>80%) entre el dato observado y el simulado.
El modelo se usó para pronosticar la posible producción total de sistemas con varias combinaciones de “wagons”, “infield tractors”, “road haulage tractors” y un “loader”. Los resultados de estas simulaciones enseñaron que la política corriente de restricción de la quota diaria asignada cada granja de 320 toneladas resultó en la baja-utilización del equipo para mayoría de las distancias viajadas. Consideraciones de alquiler y costos de posesión se usaron para identificar: (1) sistemas con el costo total más bajo para las varias distancias atravesadas, y (2) la distancia a la cual varias combinaciones se hacen más baratas para operar.

Otros resultados indicaron que vehículos que cubren más de 5 millas de la fábrica deben darles prioridad en el patio de estación de la fábrica, y que añadiendo un segundo “infield” tractor a sistemas que solo tienen uno, solo acrecenta al margen el total de producción potencial bajo las condiciones estudiadas.