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An economic evaluation of sugarcane combine harvester costs and optimal harvest schedules for Louisiana

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AN ECONOMIC EVALUATION OF SUGARCANE COMBINE HARVESTER COSTS AND OPTIMAL HARVEST SCHEDULES FOR LOUISIANA

A Thesis

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Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

In

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by
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ABSTRACT

Rising production costs, primarily associated with increasing fuel and fertilizer prices, combined with a relatively flat to slightly declining market price trend, have significantly reduced profit margins from sugarcane production in Louisiana over the past few years. Harvest operations are one area in which growers can have considerable influence on costs per unit. Estimation of current sugarcane harvest costs as well as economic evaluation of the impact of various factors on the performance and cost of this production phase are important to growers in conducting these harvest operations as efficiently and cost effectively as possible.

The general objective of this research project was to estimate the current fixed and variable costs of harvesting sugarcane in Louisiana with combine harvest units and to determine optimal harvest schedules for groups of farms delivering sugarcane to a common mill. Using 2004 input prices, average estimated harvest costs were calculated to be \$2.41 per ton for fixed expenses and \$2.79 per ton for variable expenses, resulting in a total harvest cost of \$5.20 per ton. A cost analysis conducted to evaluate the impact of increased truck waiting time at the mill on farm level harvest costs found that for every one minute of waiting time at the farm during harvest operations, the total harvest fuel and labor costs were increased by approximately \$1.30 per acre.

An integer linear programming model was developed which simulated the daily delivery of approximately 10,000 tons of harvested sugarcane with the goal of scheduling harvest operations of all farms to better coordinate trucking operations. Results of the linear programming analysis demonstrated that transport operations between farm and mill, which impacts harvest operation efficiency, could be improved with better coordination of harvest operation scheduling across a large group of farms.

CHAPTER 1. INTRODUCTION

1.1 General Introduction

Sugarcane is a major agricultural commodity in the state of Louisiana as well as in the United States. In 2004, sugarcane ranked second behind poultry in total cash receipts in Louisiana, accounting for 14.9 percent of total state cash receipts from sales of agricultural commodities (Louisiana Agricultural Statistics Service, 2005). In 2005, sugarcane in Louisiana represented 49.3 percent of total area devoted to sugarcane in the U.S., with 455,000 total acres grown for sugar and seed, producing 10,420,000 tons of cane (National Agricultural Statistics Service, 2006).

Growers face a constant challenge of trying to reduce production costs per unit of output in the face of relatively constant market prices. The average U.S. raw sugar price has varied little from year to year in response to a domestic supply management program, ranging between \$0.2046/lb to \$0.2142/lb over the 2001-2005 crop years (Economic Research Service, 2006). Over this same period, the U.S. producer prices paid index for production items, interest, taxes and wages increased by approximately 20 percent (National Agricultural Statistics Service, 2005).

In addition to higher crop yields per hectare, increasing economic efficiency in production operations can also reduce production costs. Table 1 presents a breakdown of projected sugarcane production costs for Louisiana in 2006 (Breaux and Salassi). These costs are based on a representative sugarcane farming operation with harvest through a third stubble crop. Percent of total farm area is shown for each phase of production, including fallow, seed bed preparation, planting, field operations and harvest. In this rotation, approximately 76.1

percent of the farm area would be harvested for sugar. Harvest operations represent the largest share of total farm production expenses, at 27.6 percent. Since harvest costs represent a significant portion of total farm expenses, increasing the economic efficiency of sugarcane harvest operations can have a significant impact on reducing total farm costs.

Table 1.1 Projected sugarcane production costs in Louisiana for 2006

Production phase	Percent of total farm area	Variable cost per acre	Total cost per acre	Percent of total farm cost
	(%)	*(dollars/acre)*	*(dollars/acre)*	*(%)*
Fallow / seed bed preparation	20.0	151	234	8.9
Cultured seed cane	0.1	542	553	0.7
Hand planting cultured seed cane	0.1	238	307	0.4
Harvesting whole stalk seed cane	0.4	71	120	0.9
Mechanical planting	19.4	213	265	9.7
Plant cane field operations	20.0	218	259	9.8
First stubble field operations	20.0	318	364	13.8
Second stubble field operations	20.0	325	372	14.1
Third stubble field operations	20.0	325	372	14.1
Harvest for sugar operations	76.1	119	191	27.6

1.2 Previous Research

A great deal of research has been conducted over the past several years evaluating the use of combine harvesters to harvest sugarcane in Louisiana. Much of this research has focused on management of harvest residue on fields (Kennedy et al. 2005, Kornecki et al. 2004, Richard and Johnson, 2003) and optimization of combine ground and fan speeds (Viator et al. 2004, Waguespack et al. 2003). Considerable research is being conducted in other sugarcane-producing countries focusing primarily on optimizing harvest and transport operations. This work has included optimization of harvest group scheduling (Higgins, 2002), simulation of harvest to mill delivery systems (Hansen et al., 2002), economic case study analysis of regional harvest operations (Higgins et al., 2004), as well as PC-based decision support tools to evaluate alternative harvest and transport situations (Singh and Pathak, 1994).

Published estimates of sugarcane harvest costs in other regions show values significantly less than what would be expected for Louisiana. An earlier study evaluating performance and utilization of sugarcane harvest machinery in South Africa reported harvest costs ranging from $3.23 to $3.87 per ton of sugarcane harvested (Meyer, 1999). A study which evaluated a fully mechanized combine harvest system for several farms in South Africa reported harvest and infield transport costs ranging from $2.14 to $2.92 per ton (Meyer et al., 2000). Two studies from Australia report actual harvest costs ranging between $3.69 and $5.01 per ton for the 2000 harvest season (Higgins and Muchow, 2003) and average harvest costs ranging from $3.18 to $5.39 per ton over the 1996 to 2002 period (Muscat and Agnew, 2004).

1.3 Problem Statement

The harvest of sugarcane in Louisiana represents a major cost item in the production of crop in the state. Current information on the impact of various factors on the performance and cost of this production phase is important to growers in conducting these harvest operations as efficiently and cost effectively as possible. As unloading time at the mill is a primary factor influencing the efficiency of harvest operations on the farm, developing harvest schedules for groups of farms to minimize waiting time at the mill is important for efficient and cost effective operations at both the farm and mill.

1.4 Objectives

The general objective of this research project is to estimate the current fixed and variable costs of harvesting sugarcane in Louisiana with combine harvest units and to determine optimal harvest schedules for groups of farms delivering sugarcane to a common mill.

The specific objectives of this research project are:

1. To survey a representative sample of sugarcane growers in Louisiana to collect data on factors influencing sugarcane harvest cost.
2. To estimate the current fixed and variable costs associated with harvesting sugarcane in Louisiana with a single combine harvester and complement of wagons and to perform sensitivity analysis of truck waiting time as it affects harvest cost.
3. To determine optimal harvest scheduling for a group of farms delivering harvested sugarcane to a common mill with the goal of minimizing waiting time at the mill.

1.5 Procedures

Objective one will be accomplished through a survey of sugarcane growers for the purpose of collecting information on factors influencing harvest cost. A mail survey instrument will be developed to collect data on individual farm harvest operations. Information obtained from this survey will include information on harvesters, tractors and wagons used to harvest sugarcane (number, size, age, cost, annual hours of use), information concerning typical daily harvesting hours (daily mill quota, sugarcane yield, acres harvested per day, hours in the field per day, hours actually cutting per day, average harvesting rate in tons per hour), harvest fuel and labor requirements, and other relevant factors.

Objective two will be accomplished through the use of the Mississippi State Budget Generator. This computer program will be used to estimate the per acre cost of a defined sugarcane harvest unit. Data required for harvest cost estimation will include specification of the type and size of equipment used, as well as purchase price, salvage value, repair cost, labor requirements, fuel requirements, and operation performance rates in hours per acre. Sensitivity analysis will be conducted on the impact of truck waiting time at the mill as it influences harvesting cost at the farm level.

Objective three will be accomplished through the development of a linear programming model which will simulate the harvest and delivery of sugarcane from several farms to a common mill. The purpose of this linear programming model will be to determine a harvest schedule for a group of farms which would minimize the waiting time at the mill to unload harvested sugarcane. Factors to be incorporated into this model will include farm size, daily mill quota, distance from farm to mill, and hours of mill unloading operations.

CHAPTER 2. ESTIMATION OF COMBINE HARVESTER COSTS

2.1 Introduction

Sugarcane harvest costs represent a significant portion of total sugarcane production costs. Harvest costs per acre are influenced by many factors including harvesting performance rate per acre, input costs of fuel and labor, as well as the number of acres the equipment is used over. A breakdown of current sugarcane production costs for Louisiana is presented in Table 2.1 (Salassi and Deliberto, 2007). The production phases listed follow the sequence of field operations from fallow field operations through planting and cultivation of the sugarcane crop leading to harvest. Several of the production phases listed are performed on the same acreage. For example, on sugarcane acreage to be planted in a given year, fallow / seed bed preparation, seed cane, and planting operations would be performed. On fields to be harvested for sugar, plant cane or stubble field operations (cultivation) in addition to harvest operations would be performed.

The economic theory underlying agricultural producers' decisions in general, and harvest operation decisions of sugarcane producers in particular, are based on the microeconomic theory of the firm. Microeconomic theory applicable to the research conducted in this thesis includes the assumption of profit maximization as a primary goal of the firm and the optimal combination and use of inputs to minimize the costs of producing a given level of output. Following Browning and Browning (1992), the total profit function for a firm can be expressed by the equation

$$\pi = P\,Q \; - \; C \qquad \text{or} \qquad \pi = P\,Q \; - \; \sum_{i=1}^{n} R_i\,X_i \; - \; F$$

where

π = total profit

P = price of the output produced

Q = quantity of output produced

C = total production costs

R_i = price of input i

X_i = quantity of input i used in production

F = fixed cost

The first order condition of profit maximization requires the first derivative of the total profit function to be equal to zero. Differentiating the profit function by Q yields the following condition

$$\frac{d\pi}{dQ} = P\frac{dQ}{dQ} - \frac{dC}{dQ} = 0$$

$$= P - MC = 0$$

which provides the basic decision rule for production that in order for profit to be maximized, the price of the output produced must equal the marginal cost of production.

Economic theory related to the optimal combination of inputs to produce a given level of production, under the assumption of profit maximization, is given by Pindyck and Rubinfeld (2001). For example, assuming two variable inputs of capital *(K)* and labor *(L)*, an isoquant may be defined for any given level of production which specifies the alternative combinations of capital and labor which could produce that level of output. The slope of the isoquant at any point measured as a positive value ($-\Delta K/\Delta L$) is defined as the marginal rate of technical substitution which the amount by which the quantity of one input can be reduced when one extra unit of another input is used so that the output level remains the same. An isocost cost line can be specified to depict alternative combinations of the two variable inputs which would yield the same total production cost. This isocost line may be specified as $C = wL + rK$, where C represents the total variable production cost, w is the wage rate for labor, L is the quantity of labor used in production, r is the cost of capital, and K is the quantity of capital used in production. The cost-minimizing level of input use can be found at the point where the slope of the isoquant equals the slope of the isocost line.

In the context of the research problem being analyzed here, sugarcane producers make farm management and production decisions based primarily on the goal of profit maximization. Production quantities each year are determined based on the relationship between the projected market price of raw sugar and the estimated marginal cost of producing various levels of total raw sugar output. Within the harvest season, growers are assigned a daily quota of harvested sugarcane to be delivered to a mill. The daily harvest operations of the producer are based on the theory presented, whereby input decisions are based on the goal of minimizing the cost of harvesting a given quantity of sugarcane.

For the 2007 crop year, sugarcane variable harvest costs are projected to be \$145 per acre harvested with total harvest costs projected at \$241 per acre. On a farm which harvests out through a third stubble crop, approximately 76.1 percent of the total farm acreage would be harvested for sugar in a given year. As a result, harvest costs account for approximately 32.5 percent of total farm production costs (excluding mill and land charges). Efficient harvest operations can have a significant impact on reducing both variable and fixed costs associated with owning and operating sugarcane harvesting equipment. One objective of this study was to estimate current harvesting costs for sugarcane in Louisiana. This chapter presents the procedures and results of objectives one and two of this thesis research project.

Table 2.1 Projected sugarcane production costs in Louisiana, 2007

Production phase	Percent of total farm area	Variable cost per acre	Total cost per acre	Percent of total cost
	(%)	*(dollars/acre)*	*(dollars/acre)*	*(%)*
Fallow / seed bed preparation	20.0	148	243	8.9
Cultured seed cane	0.1	540	551	0.6
Hand planting cultured seed cane	0.1	229	309	0.4
Harvesting whole stalk seed cane	0.4	67	119	0.8
Mechanical planting	19.4	203	263	9.0
Plant cane field operations	20.0	216	264	9.3
First stubble field operations	20.0	307	361	12.8
Second stubble field operations	20.0	314	368	13.0
Third stubble field operations	20.0	314	368	13.0
Harvest for sugar operations	76.1	145	241	32.5

2.2 Survey Design and Harvester Cost Estimation

The objective of this portion of the research project was to estimate the average total harvesting cost associated with using combines to harvest sugarcane in Louisiana. This work was conducted in cooperation with the Cora-Texas sugar factory located in White Castle, Louisiana. A mail survey instrument was developed to collect information about sugarcane harvesting practices and costs. The survey instrument was developed and mailed out in the summer of 2005, seeking information and data concerning the 2004 harvest season. Surveys were sent to all growers which shipped cane to Cora-Texas in 2004. Sixteen out of 37 total growers responded to the survey resulting in a response rate of 43 percent.

The survey contained questions concerning (1) number of combines used per farm, age, purchase price, hours of use in 2004, and anticipated years of useful life; (2) number of wagons used, size, purchase price, and anticipated years of useful life; (3) information on daily harvest operations in 2004 including daily quota, yield, acres harvested, hours in the field, and harvesting rate; (4) harvest fuel and labor; and (5) tractors used for harvest operations. The specific survey instrument used for this data collection process is included in the appendix of this thesis. From this data, variable and fixed harvest costs were estimated. Annual fixed costs estimated for combines included depreciation, interest and insurance. Combine depreciation expenses were estimated using years of useful life obtained from survey responses. Interest costs were estimated using a 7-percent interest rate and insurance costs were based on survey responses. Annual depreciation and interest costs were estimated for wagons, assuming a 10-year useful life, as well as that portion of tractor fixed costs applicable to harvest, based on the ratio of hours used for harvest to total annual hours of use. Variable costs included labor, fuel and repairs for combines and labor and fuel for tractors. Labor costs were estimated using the base hourly wage reported by each farm surveyed plus 27.5 percent for wage benefits. Total costs were then converted to cost per ton based on yields reported in the survey by growers for 2004.

A summary of harvesting operation responses from the survey sample are presented in Table 2.2. For the 2004 harvest season, the average acres harvested by the respondent sample were 1,530.4 acres with a range of 499.3 to 3,550.0 acres per farm. The total volume of sugarcane harvested per farm was proportional to acreage, averaging just over 45,000 tons. A typical harvesting equipment complement used in Louisiana is one combine harvester supported by three tractor and wagon sets. Harvest equipment utilized on the farms surveyed generally followed this arrangement with an average of 1.6 combines and 4.7 wagons per farm utilized for harvest.

The average daily quota for the growers surveyed was 612.0 tons of cane to be harvested and delivered to the mill per day. An average of 20.0 acres per day were harvested, with field time of 10.4 hours per day, 8.3 hours of which were time spent actually harvesting and the remaining time spent for service operations. Growers surveyed harvested at an average rate of 45.0 tons of sugarcane per combine per hour. Hours of annual used per combine ranged from 525.0 to 1,152.0 hours per season with an average annual use of 728.0 hours.

Table 2.2 Average survey responses on harvesting operations, 2004

Item	Respondent average	Minimum	Maximum
Total area harvested per farm (a*cres*)	1,530.4	499.3	3,550.0
Total volume of sugarcane harvested (*tons*)	45,284.9	10,525.1	117,000.0
Number of combines used	1.6	1.0	3.0
Number of wagons used	4.7	2.0	12.0
Daily quota (*tons*)	612.0	275.0	1,650.0
Area harvested per day (a*cres*)	20.0	8.0	50.0
Time in field per day (*hours*)	10.4	8.0	14.0
Time actually harvesting per day (*hours*)	8.3	5.0	13.0
Harvesting rate per combine (*tons* / *hour*)	45.0	30.0	75.0
Annual use of combine (*hours*)	728.0	525.0	1,152.0

2.3 Harvester Cost Estimation Results

Estimated variable and fixed harvest costs for the sample of growers surveyed is presented in Table 2.3. Total harvest fixed costs averaged $2.41 per ton of cane harvested, ranging from $1.34 to $5.13 per ton. Fixed costs on combines represented the largest component of harvest fixed costs, averaging $1.43 per ton or 59 percent of total fixed cost. Estimated average fixed costs for wagons and tractor used for harvest were $0.26 and $0.71, respectively, per ton of cane harvested. Weighted average combine variable harvesting expenses of fuel, labor and repairs were estimated at $1.27 per ton of cane harvested, with labor cost estimated at $0.34 per ton, fuel cost at $0.48 per ton, and repair cost at $0.45 per ton. Tractor variable cost for harvest operations averaged $1.52 per ton of cane harvested, with $0.81 in labor costs and $0.71 in fuel costs. Total average harvest cost was estimated at $5.20 per ton of cane harvested, ranging from $3.29 to $9.42 per ton.

Optimal use of sugarcane combines to minimize total harvest costs per unit has the most significant impact on combine fixed costs resulting from the inverse relationship between tonnage harvested and combine fixed cost per ton. Using a combine over a larger harvest area will not change the variable cost per ton of cane harvested, but will reduce the fixed cost associated with the harvesting equipment. In this study, the average annual use of combines by growers surveyed was 728 hours per year. An annual use of 1,000 hours per year would have lowered combine fixed cost by $0.60 per ton of cane harvested.

Table 2.3 Average harvest cost per ton of sugarcane harvested from survey sample, 2004

Cost item	Weighted average cost	Minimum	Maximum
	(dollars / harvested ton)		
Combine fixed cost	1.43	0.74	3.56
Wagon fixed cost	0.26	0.15	0.43
Tractor fixed cost	0.71	0.29	2.16
Total harvest fixed cost	2.41	1.34	5.13
Combine labor cost	0.34	0.11	0.56
Combine fuel cost 1/	0.48	0.21	0.93
Combine repair cost	0.45	0.19	2.50
Tractor labor cost	0.81	0.48	1.39
Tractor fuel cost 1/	0.71	0.22	2.18
Total harvest variable cost	2.79	1.89	5.34
Total harvest cost	5.20	3.29	9.42

1/ 2004 diesel price at $1.45 per gallon.

Harvest of sugarcane represents a large capital investment for sugarcane farms and also represents a significant share of total farm production expenses. Optimal use of combine harvesters to minimize sugarcane harvest costs is primarily dependent on the amount of area over which a machine is used, thereby reducing fixed cost per unit of output. The challenge confronting growers in Louisiana is how to arrange harvest operations to achieve desired cost savings. Options include using a harvester over more acres on a individual farm, sharing harvesting equipment with a small number of growers in a fairly localized area, or utilizing a more broad scale group harvest type of arrangement. Given the diversity of sugarcane farming operations in Louisiana, the most optimal harvesting arrangement is expected to vary across growers.

2.4 Impact of Increased Waiting Time on Harvest Costs

One factor which has a significant influence on actual sugarcane harvest cost per acre is the impact of waiting time on harvest operations. As the number of trucks arriving at a mill to unload harvested sugarcane from farms in a given time period increases, the time required for a truck to be sampled at the core lab, unload in the mill yard, and return to the farm also increases. In some cases, this increased turnaround time at mill causes harvest operations at the farm to stop in order to wait for a truck to arrive at the farm. This possible waiting time increases actual harvest costs per acre primarily due to the additional fuel and labor costs associated with the stoppage of harvest operations to wait for a truck to arrive at the farm.

Estimated harvest costs for sugarcane in Louisiana for the 2007 crop year are presented in Table 2.4. These costs represent the estimated variable and fixed costs of sugarcane harvest operations and include estimates for both the combine harvester and three supporting tractor and wagon complements. Variable harvest costs are projected at $144.54 per harvested acre for 2007 and include charges for fuel, labor, repairs and interest on operating capital. Fixed harvest costs for 2007 are projected at $96.78 per acre and include depreciation and interest charges on machinery used in the harvest operation. Total sugarcane harvest costs are estimated at $241.32 per harvested acre.

Estimated costs for individual harvest operations are shown in Table 2.5. Specific operations itemized in the budget include a combine harvester, three tractor and wagon sets, and on pass with a drain cleaner. The performance rate specified for the harvester and wagons is 0.70 hours per acre. In other words, harvest costs are estimated based on the assumption that it takes 0.70 hours (42 minutes) to harvest one acre of sugarcane. The critical assumption here is that this performance rate assumes no increased waiting time to delay harvest operations.

Table 2.4 Estimated sugarcane harvest costs per acre, Louisiana, 2007

Item	Unit	Price	Quantity	Amount
		(dollars)		(dollars/acre)
Direct Expenses:				
Operator Labor				
Self-Propelled	hour	15.30	0.77	11.78
Hired Labor				
Tractors	hour	9.60	2.39	22.94
Diesel Fuel				
Tractors	gal	2.10	18.14	38.09
Self-Propelled	gal	2.10	8.40	17.64
Repair & Maintenance				
Implements	acre	14.14	1.00	14.14
Tractors	acre	7.29	1.00	7.29
Self-Propelled	acre	22.21	1.00	22.21
Interest on operating cap.	acre	10.45	1.00	10.45
Total Direct Expenses				144.54
Fixed Expenses:				
Implements	acre	12.60	1.00	12.60
Tractors	acre	52.92	1.00	52.92
Self-Propelled	acre	31.26	1.00	31.26
Total Fixed Expenses				96.78
Total Specified Expenses				241.32

Source: Salassi and Deliberto (2007).

Table 2.5 Estimated sugarcane harvest operation costs per acre, Louisiana, 2007

		Power Unit		Equipment		Labor		
	Perf. rate	Direct cost	Fixed cost	Direct cost	Fixed cost	Hours	Labor cost	Total cost
Combine Harvester	0.70	39.85	31.26	-	-	0.77	11.78	82.89
Billet Wagon 1	0.70	14.88	17.43	4.67	4.15	0.77	7.39	48.52
Billet Wagon 2	0.70	14.88	17.43	4.67	4.15	0.77	7.39	48.52
Billet Wagon 3	0.70	14.88	17.43	4.67	4.15	0.77	7.39	48.52
Drain Cleaner	0.08	0.74	0.63	0.13	0.15	0.08	0.77	2.42
Interest on op. cap.								10.45
Totals		85.23	84.18	14.14	12.60	3.16	34.72	241.32

Source: Salassi and Deliberto (2007).

In order to evaluate the impact of increases in waiting time on harvest cost, an analysis was conducted to estimate changes in harvest cost resulting from increased waiting time by adjusting the performance rate of harvest operations. This analysis focused on the fuel and labor costs associated with the harvester and tractors and wagons since these are the cost items most directly impacted by waiting time. To simulate a range of possible waiting times, harvest time was increased from five to thirty minutes per acre to represent the stoppage of harvest operations to wait for a truck to arrive. This resulted in an adjustment of the harvest performance rate from 0.70 hours per acre to values between a range of 0.78 and 1.20 hours per acre. Fuel consumption of the harvester and tractors were adjusted using a factor of 40 percent to reflect idle speed. Labor for the combine harvester operator was charged at a rate of $15.30 per hour and labor for tractor operators was charged at a rate of $9.60 per hour. Results of this cost analysis is presented in Table 2.6.

Fuel and labor cost of harvest operations, assuming no waiting time, is estimated at $54.63 per acre. A five minute increase in waiting time was estimated to increase harvest cost by $6.24 per acre to $60.87. This represents an 11.4 percent increase in harvest fuel and labor cost. A thirty minute increase in waiting time was estimated to increase harvest costs by $39.02 per acre. Although a farm would probably not average this amount of waiting time over an entire farm during the harvest season, this type of scenario could easily exist on a few days of harvest. This analysis indicates that for every one minute of additional waiting time, harvest fuel and labor costs increase by approximately $1.30 per acre.

Table 2.6 Estimated impact of increasing waiting time on sugarcane harvest costs, 2007

		Variable Harvest Cost			Cost Change	
Increased Waiting Time Scenarios	Adjusted Performance Rate (hours/acre)	Fuel ($/acre)	Labor ($/acre)	Total ($/acre)	Dollars per Acre	%
0 minutes per acre:						
Combine Harvester	0.70	7.06	11.78	18.84		
Billet Wagons (3)	0.70	13.62	22.17	35.79		
Total Additional Cost				54.63	-	-
5 minutes per acre:						
Combine Harvester	0.78	7.86	13.13	20.99		
Billet Wagons (3)	0.78	15.18	24.72	39.87		
Total Additional Cost				60.87	6.24	11.4
10 minutes per acre:						
Combine Harvester	0.87	8.77	14.64	23.41		
Billet Wagons (3)	0.87	16.92	27.57	44.49		
Total Additional Cost				67.90	13.27	24.3
15 minutes per acre:						
Combine Harvester	0.95	9.58	15.99	25.56		
Billet Wagons (3)	0.95	18.48	30.09	48.57		
Total Additional Cost				74.14	19.51	35.7
20 minutes per acre:						
Combine Harvester	1.03	10.38	17.33	27.72		
Billet Wagons (3)	1.03	20.04	32.64	52.68		
Total Additional Cost				80.39	25.75	47.1
25 minutes per acre:						
Combine Harvester	1.12	11.29	18.85	30.14		
Billet Wagons (3)	1.12	21.78	35.49	57.27		
Total Additional Cost				87.41	32.78	60.0
30 minutes per acre:						
Combine Harvester	1.20	12.10	20.20	32.29		
Billet Wagons (3)	1.20	23.34	38.01	61.35		
Total Additional Cost				93.65	39.02	71.4

CHAPTER 3. EVALUATION OF OPTIMAL HARVEST SCHEDULES

3.1 Introduction

The analysis in the previous chapter illustrated the impact of increased waiting time on sugarcane harvest costs. In order to reduce waiting time at the farm, truck waiting time at the mills must be reduced. One way to accomplish this is to schedule harvest and delivery times among farms delivering to a common mill with the goal of spreading out the deliveries of harvested sugarcane over the day. Several mills in Louisiana are investigating the possibility of scheduling harvests for farms delivering to those mills. Given the range in farm sizes as well as the varying distances hauled from farm to mill, the challenge has been to develop a harvest schedule which can take these factors into consideration while still developing a harvest schedule which can minimize waiting time of loaded trucks at the mill. This chapter presents a discussion of a linear programming model which has been developed to address this problem along with results of simulated sugarcane distribution scenarios illustrating the impact of farm size and distance from the mill on optimal harvest schedules.

3.2 Linear Programming Model

An integer linear programming model was developed which would be capable of determining an optimal harvest schedule for a group of farms delivering to a common mill with the objective of minimizing the waiting time of trucks delivering to the mill. The linear programming model simulates delivery of harvested sugarcane by truck and trailer over the course of one day during the grinding season. Alternative harvest starting times were included to represent potential harvest schedules available to farms. The objective function of the linear programming model minimizes the sum of truck loads over the course of the day exceeding a specified threshold.

A total of 360 trucks loads were assumed to be delivered per day to the mill, representing approximately 10,000 tons of sugarcane harvested daily. Two farm sizes were simulated in the model: one with six loads per day and the other with twelve loads per day. Three distances from farm to mill, in minutes of travel time, were simulated: 15 minutes, 30 minutes and 45 minutes. Harvest time to load one truck was assumed to be 45 minutes. All harvest and transportation operations in the model were included in 15 minutes blocks of time. For the farms with six daily loads, thirty-three alternative harvest schedules were included in the model, with the first harvest schedule starting at 6:00 a.m., remaining harvest schedules starting at 15 minute intervals and the last harvest schedule of the day starting at 2:00 p.m. For the farms with twelve daily loads, fifteen alternative harvest schedules were included in the model, with the first harvest schedule starting at 6:00 a.m., remaining harvest schedules starting at 15 minute intervals and the last harvest schedule of the day starting at 9:30 a.m.

The general form of the specific integer linear programming model used in this analysis is specified as:

$$Min \quad T = \sum_{h=1}^{14} EXUM_h$$

s.t.

(1) $A1ST_a - A2ST_{a+3} = 0 \quad for\ a = 1\ to\ 33$
(2) $A1ST_a - A3ST_{a+6} = 0$
(3) $A1ST_a - A4ST_{a+9} = 0$
(4) $A1ST_a - A5ST_{a+12} = 0$
(5) $A1ST_a - A6ST_{a+15} = 0$

(6) $B1ST_b - B2ST_{b+3} = 0 \quad for\ b = 1\ to\ 15$
(7) $B1ST_b - B3ST_{b+6} = 0$
(8) $B1ST_b - B4ST_{b+9} = 0$
(9) $B1ST_b - B5ST_{b+12} = 0$
(10) $B1ST_b - B6ST_{b+15} = 0$

(11) $B1ST_b - B7ST_{b+18} = 0$
(12) $B1ST_b - B8ST_{b+21} = 0$
(13) $B1ST_b - B9ST_{b+24} = 0$
(14) $B1ST_b - B10ST_{b+27} = 0$
(15) $B1ST_b - B11ST_{b+30} = 0$
(16) $B1ST_b - B12ST_{b+33} = 0$

(17) $C1ST_c - C2ST_{c+3} = 0 \quad for\ c = 1\ to\ 33$
(18) $C1ST_c - C3ST_{c+6} = 0$
(19) $C1ST_c - C4ST_{c+9} = 0$
(20) $C1ST_c - C5ST_{c+12} = 0$
(21) $C1ST_c - C6ST_{c+15} = 0$

(22) $D1ST_d - D2ST_{d+3} = 0 \quad for\ d = 1\ to\ 15$
(23) $D1ST_d - D3ST_{d+6} = 0$
(24) $D1ST_d - D4ST_{d+9} = 0$
(25) $D1ST_d - D5ST_{d+12} = 0$
(26) $D1ST_d - D6ST_{d+15} = 0$
(27) $D1ST_d - D7ST_{d+18} = 0$
(28) $D1ST_d - D8ST_{d+21} = 0$
(29) $D1ST_d - D9ST_{d+24} = 0$
(30) $D1ST_d - D10ST_{d+27} = 0$
(31) $D1ST_d - D11ST_{d+30} = 0$
(32) $D1ST_d - D12ST_{d+33} = 0$

(33) $E1ST_e - E2ST_{e+3} = 0 \quad for\ e = 1\ to\ 33$
(34) $E1ST_e - E3ST_{e+6} = 0$
(35) $E1ST_e - E4ST_{e+9} = 0$
(36) $E1ST_e - E5ST_{e+12} = 0$
(37) $E1ST_e - E6ST_{e+15} = 0$

(38) $F1ST_f - F2ST_{f+3} = 0 \quad for\ f = 1\ to\ 15$
(39) $F1ST_f - F3ST_{f+6} = 0$
(40) $F1ST_f - F4ST_{f+9} = 0$
(41) $F1ST_f - F5ST_{f+12} = 0$
(42) $F1ST_f - F6ST_{f+15} = 0$

(43) $F1ST_f - F7ST_{f+18} = 0$
(44) $F1ST_f - F8ST_{f+21} = 0$
(45) $F1ST_f - F9ST_{f+24} = 0$
(46) $F1ST_f - F10ST_{f+27} = 0$
(47) $F1ST_f - F11ST_{f+30} = 0$
(48) $F1ST_f - F12ST_{f+33} = 0$

(49) $\sum_{a=1}^{33} A1ST_a = A$
(50) $\sum_{b=1}^{15} B1ST_b = B$
(51) $\sum_{c=1}^{33} C1ST_c = C$
(52) $\sum_{d=1}^{15} D1ST_d = D$
(53) $\sum_{e=1}^{33} E1ST_e = E$
(54) $\sum_{f=1}^{15} F1ST_f = F$

(55) $A1ST_a - A1UM_{a+4} = 0 \quad for\ a = 1\ to\ 33$
(56) $A2ST_{a+3} - A2UM_{a+7} = 0$
(57) $A3ST_{a+6} - A3UM_{a+10} = 0$
(58) $A4ST_{a+9} - A4UM_{a+13} = 0$
(59) $A5ST_{a+12} - A5UM_{a+16} = 0$
(60) $A6ST_{a+15} - A6UM_{a+19} = 0$

(61) $B1ST_b - B1UM_{b+4} = 0 \quad for\ b = 1\ to\ 15$
(62) $B2ST_{b+3} - B2UM_{b+7} = 0$
(63) $B3ST_{b+6} - B3UM_{b+10} = 0$
(64) $B4ST_{b+9} - B4UM_{b+13} = 0$
(65) $B5ST_{b+12} - B5UM_{b+16} = 0$
(66) $B6ST_{b+15} - B6UM_{b+19} = 0$
(67) $B7ST_{b+18} - B7UM_{b+22} = 0$
(68) $B8ST_{b+21} - B8UM_{b+25} = 0$
(69) $B9ST_{b+24} - B9UM_{b+28} = 0$

(70) $B10ST_{b+27} - B10UM_{b+31} = 0$
(71) $B11ST_{b+30} - B11UM_{b+34} = 0$
(72) $B12ST_{b+33} - B12UM_{b+37} = 0$

(73) $C1ST_{c} - C1UM_{c+5} = 0 \quad for\ c = 1\ to\ 33$
(74) $C2ST_{c+3} - C2UM_{a+8} = 0$
(75) $C3ST_{c+6} - C3UM_{c+11} = 0$
(76) $C4ST_{c+9} - C4UM_{c+14} = 0$
(77) $C5ST_{c+12} - C5UM_{c+17} = 0$
(78) $C6ST_{c+15} - C6UM_{c+20} = 0$

(79) $D1ST_{d} - D1UM_{d+5} = 0 \quad for\ d = 1\ to\ 15$
(80) $D2ST_{d+3} - D2UM_{d+8} = 0$
(81) $D3ST_{d+6} - D3UM_{d+11} = 0$
(82) $D4ST_{d+9} - D4UM_{d+14} = 0$
(83) $D5ST_{d+12} - D5UM_{d+17} = 0$
(84) $D6ST_{d+15} - D6UM_{d+20} = 0$
(85) $D7ST_{d+18} - D7UM_{d+23} = 0$
(86) $D8ST_{d+21} - D8UM_{d+26} = 0$
(87) $D9ST_{d+24} - D9UM_{d+29} = 0$
(88) $D10ST_{d+27} - D10UM_{d+32} = 0$
(89) $D11ST_{d+30} - D11UM_{d+35} = 0$
(90) $D12ST_{d+33} - D12UM_{d+38} = 0$

(91) $E1ST_{e} - E1UM_{e+6} = 0 \quad for\ e = 1\ to\ 33$
(92) $E2ST_{e+3} - E2UM_{e+9} = 0$
(93) $E3ST_{e+6} - E3UM_{e+12} = 0$
(94) $E4ST_{e+9} - E4UM_{e+15} = 0$
(95) $E5ST_{e+12} - E5UM_{e+18} = 0$
(96) $E6ST_{e+15} - E6UM_{e+21} = 0$

(97) $F1ST_{f} - F1UM_{f+6} = 0 \quad for\ f = 1\ to\ 15$
(98) $F2ST_{f+3} - F2UM_{f+9} = 0$
(99) $F3ST_{f+6} - F3UM_{f+12} = 0$
(100) $F4ST_{f+9} - F4UM_{f+15} = 0$
(101) $F5ST_{f+12} - F5UM_{f+18} = 0$

(102) $F6ST_{f+15} - F6UM_{f+21} = 0$

(103) $F7ST_{f+18} - F7UM_{f+24} = 0$

(104) $F8ST_{f+21} - F8UM_{f+27} = 0$

(105) $F9ST_{f+24} - F9UM_{f+30} = 0$

(106) $F10ST_{f+27} - F10UM_{f+33} = 0$

(107) $F11ST_{f+30} - F11UM_{f+36} = 0$

(108) $F12ST_{f+33} - F12UM_{f+39} = 0$

(109) $DFUM_1 - EXUM_1 = 30$

(110)
$$\begin{aligned}
&A1UM_5 + B1UM_5 + A1UM_6 + B1UM_6 + A1UM_7 + B1UM_7 + A1UM_8 + A2UM_8\\
&+ B1UM_8 + B2UM_8 + C1UM_6 + C1UM_7 + C1UM_8 + D1UM_6 + D1UM_7\\
&+ D1UM_8 + E1UM_7 + E1UM_8 + F1UM_7 + F1UM_8 + DFUM_2 - EXUM_2 = 30
\end{aligned}$$

(111)
$$\begin{aligned}
&A1UM_9 + B1UM_9 + A2UM_9 + B2UM_9 + A1UM_{10} + B1UM_{10} + A2UM_{10} + B2UM_{10}\\
&+ A1UM_{11} + B1UM_{11} + A2UM_{11} + B2UM_{11} + A3UM_{11} + B3UM_{11} + A1UM_{12} + B1UM_{12}\\
&+ A2UM_{12} + B2UM_{12} + A3UM_{12} + B3UM_{12} + C1UM_9 + C2UM_9 + C1UM_{10} + C2UM_{10}\\
&+ C1UM_{11} + C2UM_{11} + C1UM_{12} + C2UM_{12} + C3UM_{12} + D1UM_9 + D2UM_9 + D1UM_{10}\\
&+ D2UM_{10} + D1UM_{11} + D2UM_{11} + D1UM_{12} + D2UM_{12} + D3UM_{12} + E1UM_9 + F1UM_9\\
&+ E1UM_{10} + F1UM_{10} + E2UM_{10} + F2UM_{10} + E1UM_{11} + F1UM_{11} + E2UM_{11} + F2UM_{11}\\
&+ E1UM_{12} + F1UM_{12} + E2UM_{12} + F2UM_{12} + DFUM_3 - EXUM_3 = 30
\end{aligned}$$

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(121)
$$\begin{aligned}
&A5UM_{49} + A6UM_{49} + B11UM_{49} + B12UM_{49} + A6UM_{50} + B12UM_{50} + A6UM_{51}\\
&+ B12UM_{51} + A6UM_{52} + B12UM_{52} + C5UM_{49} + C6UM_{49} + C5UM_{50} + C6UM_{50}\\
&+ C6UM_{51} + C6UM_{52} + D11UM_{49} + D12UM_{49} + D11UM_{50} + D12UM_{50} + D12UM_{51}\\
&+ D12UM_{52} + E5UM_{49} + E6UM_{49} + F11UM_{49} + F12UM_{49} + E5UM_{50} + E6UM_{50}\\
&+ F11UM_{50} + F12UM_{50} + E5UM_{51} + E6UM_{51} + F11UM_{51} + F12UM_{51} + E6UM_{52}\\
&+ F12UM_{52} + DFUM_{13} - EXUM_{13} = 30
\end{aligned}$$

(122)
$$\begin{aligned}
&C6UM_{53} + D12UM_{53} + E6UM_{53} + F12UM_{53} + E6UM_{54} + F12UM_{54}\\
&+ DFUM_{14} - EXUM_{14} = 30
\end{aligned}$$

$$\begin{aligned}&A1UM_5 + A1UM_6 + B1UM_5 + B1UM_6 + C1UM_6 + C1UM_7 + C1UM_8\\&+ D1UM_6 + D1UM_7 + D1UM_8 + E1UM_7 + E1UM_8 + E1UM_9 + E1UM_{10}\\&+ F1UM_7 + F1UM_8 + F1UM_9 + F1UM_{10} - TRUCKS \leq 0\end{aligned}\tag{123}$$

$$\begin{aligned}&A1UM_5 + A1UM_6 + A1UM_7 + B1UM_5 + B1UM_6 + B1UM_7 + C1UM_6 + C2UM_9\\&+ C1UM_7 + C1UM_8 + C1UM_9 + D1UM_6 + D2UM_9 + D1UM_7 + D1UM_8\\&+ D1UM_9 + E1UM_7 + E2UM_{10} + E1UM_8 + E2UM_{11} + E1UM_9 + E1UM_{10}\\&+ E1UM_{11} + F1UM_7 + F2UM_{10} + F1UM_8 + F2UM_{11} + F1UM_9\\&+ F1UM_{10} + F1UM_{11} - TRUCKS \leq 0\end{aligned}\tag{124}$$

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$$E6UM_{54} + F12UM_{54} - TRUCKS \leq 0 \tag{176}$$

and

$$\left.\begin{aligned}&A1ST_1, A1ST_2, \ldots A1ST_{33}, B1ST_1, B1ST_2, \ldots B1ST_{15},\\&C1ST_1, C1ST_2, \ldots C1ST_{33}, D1ST_1, D1ST_2, \ldots D1ST_{15},\\&E1ST_1, E1ST_2, \ldots E1ST_{33}, F1ST_1, F1ST_2, \ldots F1ST_{15},\end{aligned}\right. \text{ are integer}$$

where

$A1ST_a$ = number of farms in group A starting harvest of load 1 in time period a

$A2ST_a$ = number of farms in group A starting harvest of load 2 in time period a

$A3ST_a$ = number of farms in group A starting harvest of load 3 in time period a

$A4ST_a$ = number of farms in group A starting harvest of load 4 in time period a

$A5ST_a$ = number of farms in group A starting harvest of load 5 in time period a

$A6ST_a$ = number of farms in group A starting harvest of load 6 in time period a

$B1ST_b$ = number of farms in group B starting harvest of load 1 in time period b

$B2ST_b$ = number of farms in group B starting harvest of load 2 in time period b

$B3ST_b$ = number of farms in group B starting harvest of load 3 in time period b

$B4ST_b$ = number of farms in group B starting harvest of load 4 in time period b

$B5ST_b$ = number of farms in group B starting harvest of load 5 in time period b

$B6ST_b$ = number of farms in group B starting harvest of load 6 in time period b

$B7ST_b$ = number of farms in group B starting harvest of load 7 in time period b

$B8ST_b$ = number of farms in group B starting harvest of load 8 in time period b

$B9ST_b$ = number of farms in group B starting harvest of load 9 in time period b

$B10ST_b$ = number of farms in group B starting harvest of load 10 in time period b

$B11ST_b$ = number of farms in group B starting harvest of load 11 in time period b

$B12ST_b$ = number of farms in group B starting harvest of load 12 in time period b

$C1ST_c$ = number of farms in group C starting harvest of load 1 in time period c

$C2ST_c$ = number of farms in group C starting harvest of load 2 in time period c

$C3ST_c$ = number of farms in group C starting harvest of load 3 in time period c

$C4ST_c$ = number of farms in group C starting harvest of load 4 in time period c

$C5ST_c$ = number of farms in group C starting harvest of load 5 in time period c

$C6ST_c$ = number of farms in group C starting harvest of load 6 in time period c

$D1ST_d$ = number of farms in group D starting harvest of load 1 in time period d

$D2ST_d$ = number of farms in group D starting harvest of load 2 in time period d

$D3ST_d$ = number of farms in group D starting harvest of load 3 in time period d

$D4ST_d$ = number of farms in group D starting harvest of load 4 in time period d

$D5ST_d$ = number of farms in group D starting harvest of load 5 in time period d

$D6ST_d$ = number of farms in group D starting harvest of load 6 in time period d

$D7ST_d$ = number of farms in group D starting harvest of load 7 in time period d

$D8ST_d$ = number of farms in group D starting harvest of load 8 in time period d

$D9ST_d$ = number of farms in group D starting harvest of load 9 in time period d

$D10ST_d$ = number of farms in group D starting harvest of load 10 in time period d

$D11ST_d$ = number of farms in group D starting harvest of load 11 in time period d

$D12ST_d$ = number of farms in group D starting harvest of load 12 in time period d

$E1ST_e$ = number of farms in group E starting harvest of load 1 in time period e

$E2ST_e$ = number of farms in group E starting harvest of load 2 in time period e

$E3ST_e$ = number of farms in group E starting harvest of load 3 in time period e

$E4ST_e$ = number of farms in group E starting harvest of load 4 in time period e

$E5ST_e$ = number of farms in group E starting harvest of load 5 in time period e

$E6ST_e$ = number of farms in group E starting harvest of load 6 in time period e

$F1ST_f$ = number of farms in group F starting harvest of load 1 in time period f

$F2ST_f$ = number of farms in group F starting harvest of load 2 in time period f

$F3ST_f$ = number of farms in group F starting harvest of load 3 in time period f

$F4ST_f$ = number of farms in group F starting harvest of load 4 in time period f

$F5ST_f$ = number of farms in group F starting harvest of load 5 in time period f

$F6ST_f$ = number of farms in group F starting harvest of load 6 in time period f

$F7ST_f$ = number of farms in group F starting harvest of load 7 in time period f

$F8ST_f$ = number of farms in group F starting harvest of load 8 in time period f

$F9ST_f$ = number of farms in group F starting harvest of load 9 in time period f

$F10ST_f$ = number of farms in group F starting harvest of load 10 in time period f

$F11ST_f$ = number of farms in group F starting harvest of load 11 in time period f

$F12ST_f$ = number of farms in group F starting harvest of load 12 in time period f

$A1UM_a$ = number of farms in group A unloading load 1 at the mill in time period a

$A2UM_a$ = number of farms in group A unloading load 2 at the mill in time period a

$A3UM_a$ = number of farms in group A unloading load 3 at the mill in time period a

$A4UM_a$ = number of farms in group A unloading load 4 at the mill in time period a

$A5UM_a$ = number of farms in group A unloading load 5 at the mill in time period a

$A6UM_a$ = number of farms in group A unloading load 6 at the mill in time period a

$B1UM_b$ = number of farms in group B unloading load 1 at the mill in time period b

$B2UM_b$ = number of farms in group B unloading load 2 at the mill in time period b

$B3UM_b$ = number of farms in group B unloading load 3 at the mill in time period b

$B4UM_b$ = number of farms in group B unloading load 4 at the mill in time period b

$B5UM_b$ = number of farms in group B unloading load 5 at the mill in time period b

$B6UM_b$ = number of farms in group B unloading load 6 at the mill in time period b

$B7UM_b$ = number of farms in group B unloading load 7 at the mill in time period b

$B8UM_b$ = number of farms in group B unloading load 8 at the mill in time period b

$B9UM_b$ = number of farms in group B unloading load 9 at the mill in time period b

$B10UM_b$ = number of farms in group B unloading load 10 at the mill in time period b

$B11UM_b$ = number of farms in group B unloading load 11 at the mill in time period b

$B12UM_b$ = number of farms in group B unloading load 12 at the mill in time period b

$C1UM_c$ = number of farms in group C unloading load 1 at the mill in time period c

$C2UM_c$ = number of farms in group C unloading load 2 at the mill in time period c

$C3UM_c$ = number of farms in group C unloading load 3 at the mill in time period c

$C4UM_c$ = number of farms in group C unloading load 4 at the mill in time period c

$C5UM_c$ = number of farms in group C unloading load 5 at the mill in time period c

$C6UM_c$ = number of farms in group C unloading load 6 at the mill in time period c

$D1UM_d$ = number of farms in group D unloading load 1 at the mill in time period d

$D2UM_d$ = number of farms in group D unloading load 2 at the mill in time period d

$D3UM_d$ = number of farms in group D unloading load 3 at the mill in time period d

$D4UM_d$ = number of farms in group D unloading load 4 at the mill in time period d

$D5UM_d$ = number of farms in group D unloading load 5 at the mill in time period d

$D6UM_d$ = number of farms in group D unloading load 6 at the mill in time period d

$D7UM_d$ = number of farms in group D unloading load 7 at the mill in time period d

$D8UM_d$ = number of farms in group D unloading load 8 at the mill in time period d

$D9UM_d$ = number of farms in group D unloading load 9 at the mill in time period d

$D10UM_d$ = number of farms in group D unloading load 10 at the mill in time period d

$D11UM_d$ = number of farms in group D unloading load 11 at the mill in time period d

$D12UM_d$ = number of farms in group D unloading load 12 at the mill in time period d

$E1UM_e$ = number of farms in group E unloading load 1 at the mill in time period e

$E2UM_e$ = number of farms in group E unloading load 2 at the mill in time period e

$E3UM_e$ = number of farms in group E unloading load 3 at the mill in time period e

$E4UM_e$ = number of farms in group E unloading load 4 at the mill in time period e

$E5UM_e$ = number of farms in group E unloading load 5 at the mill in time period e

$E6UM_e$ = number of farms in group E unloading load 6 at the mill in time period e

$F1UM_f$ = number of farms in group F unloading load 1 at the mill in time period f

$F2UM_f$ = number of farms in group F unloading load 2 at the mill in time period f

$F3UM_f$ = number of farms in group F unloading load 3 at the mill in time period f

$F4UM_f$ = number of farms in group F unloading load 4 at the mill in time period f

$F5UM_f$ = number of farms in group F unloading load 5 at the mill in time period f

$F6UM_f$ = number of farms in group F unloading load 6 at the mill in time period f

$F7UM_f$ = number of farms in group F unloading load 7 at the mill in time period f

$F8UM_f$ = number of farms in group F unloading load 8 at the mill in time period f

$F9UM_f$ = number of farms in group F unloading load 9 at the mill in time period f

$F10UM_f$ = number of farms in group F unloading load 10 at the mill in time period f

$F11UM_f$ = number of farms in group F unloading load 11 at the mill in time period f

$F12UM_f$ = number of farms in group F unloading load 12 at the mill in time period f

A = number of farms in group A

B = number of farms in group B

C = number of farms in group C

D = number of farms in group D

E = number of farms in group E

F = number of farms in group F

$DFUM_a$ = number of loads unloading at the mill in deficit of 30 in hourly time period a

$EXUM_a$ = number of loads unloading at the mill in excess of 30 in hourly time period a

$TRUCKS$ = number of trucks required to cover all harvest and delivery schedules.

The objective function minimizes the number of truckloads of harvested sugarcane unloading in a given hour (h) which exceed an hourly target of 30 trucks ($EXUM_h$) and are summed over a 14-hour delivery time period. Actual deliveries are over a 12.5 hour time frame, hence the 30 truck per hour target was determined by dividing 360 daily loads by an approximate 12 hour delivery time frame. This objective function is modeled to serve as a proxy for minimization of truck waiting time at the mill by spreading hourly deliveries more evenly over the daily mill delivery time window.

Constraints (1) through (5) ensure that when one or more farms in Group A start harvesting the first truckload under a given harvest schedule, that those farms will continue with that harvest schedule through truckloads 2-6. Group A represents farms with six daily loads and are located 15 minutes from the mill. With harvest time for one truckload assumed to be 45 minutes, harvest of the succeeding truckload will start three time periods after the starting time of the current load, where $A1ST_a$ represents the number of Group A farms starting to harvest their first daily load in time period a and $A2ST_{a+3}$ represents the same number of farms in Group A starting to harvest their second daily load in time period a+3. These constraints are repeated for all thirty-three possible daily harvest schedules for Group A.

Constraints (6) through (16) ensure that when one or more farms in Group B start harvesting the first truckload under a given harvest schedule, that those farms will continue with that harvest schedule through truckloads 2-12. Group B represents farms with twelve daily loads and are located 15 minutes from the mill. With harvest time for one truckload assumed to be 45 minutes, harvest of the succeeding truckload will start three time periods after the starting time of the current load, where $B1ST_b$ represents the number of Group B farms starting to harvest their first daily load in time period b and $B2ST_{b+3}$ represents the same number of farms in Group B starting to harvest their second daily load in time period B+3. These constraints are repeated for all fifteen possible daily harvest schedules for Group B.

Similar constraints are included in the model for the other four groups of farms for the same purpose of ensuring that once farms start on a given harvest schedule that they continue with that harvest schedule until all daily loads are harvested. Group C (constraints 17-21) represents farms with six daily loads located 30 minutes from the mill. Group D (constraints 22-32) represents farms with twelve daily loads located 30 minutes from the mill. Group E (constraints 33-37) represents farms with six daily loads located 45 minutes from the mill. Group F (constraints 38-48) represents farms with twelve daily loads located 45 minutes from the mill. Constraints 49-54 specify the total number of sugarcane farms in each group, with *A* equal to the number of farms in Group A, *B* equal to the number of farms in Group B, *C* equal to the number of farms in Group C, *D* equal to the number of farms in Group D, *E* equal to the number of farms in Group E, and *F* equal to the number of farms in Group F.

For each possible harvest schedule, a set of constraints were included in the model to specify what time period a particular truckload would be unloading at the mill given the time period when harvest of that load was started. For example, if $A1ST_a$ represents the time period in which the first load of Group A was harvested, $A1UM_{a+4}$ represents the time period when that truckload would be unloaded at the mill. The model assumes that a particular truckload would be unloaded at the mill in the immediate time period following its travel to the mill. Constraints 55-60 specify mill unloading time period for Group A farms, constraints 61-72 specify mill loading time period for Group B farms, constraints 73-78 specify mill loading time period for Group C farms, constraints 79-90 specify mill loading time period for Group D farms, constraints 91-96 specify mill loading time period for Group E farms, and constraints 97-108 specify mill loading time period for Group F farms.

The next set of constraints counts the total number of trucks unloading at the mill in a given hour and determines the deficit or excess loads from a target of 30 truckloads per hour. Constraint 109 represents the first hour of possible delivery and unloading at the mill, for which no trucks arrive given the harvest schedules and distances included in the model. Constraint 110 represents the second hour of possible delivery and unloading at the mill. Variables representing unloading the mill in periods 5, 6, 7 and 8 from all six possible farm groups are included and set equal to the hourly delivery and unloading target of 30 trucks per hour. The variable $DFUM_2$ measures the number of trucks unloading in the second hour in deficit of the 30 per hour target. The variable $EXUM_2$ measures the number of trucks unloading in the second hour in excess of the 30 per hour target. These constraints are continued through the fourteenth delivery hour (constraint 122).

The final set of constraints in the model (constraints 123-176) count the number of total trucks in use during each 15-minute time period. Variables included in each constraint represent trucks traveling to farms, trucks being loaded at farms, trucks traveling back to the mill, and trucks being unloaded at the mill. The variable *TRUCKS* included in each constraint will represent the minimum number of trucks required to achieve all deliveries for the specific harvest schedule determined by the optimal solution.

3.3 Sugarcane Distribution Scenarios

Six different grower distribution scenarios were evaluated using the specified linear programming model with the objective of determining an optimal harvest schedule for all farms which would minimize waiting time at the mill. These scenarios are listed in Table 3.1. Each scenario was comprised of 360 daily loads, although the size of farm and distance from the mill were varied. The first two scenarios represent the situation where all farms shipping to a mill are in relatively close proximity to the mill. Scenario 1 included 60 growers who were located 15 minutes from the mill with six daily loads to be harvested and delivered. Scenario 2 included 45 growers who were located 15 minutes from the mill, 30 of which had six daily loads and 15 of which had twelve daily loads.

Four additional grower distribution scenarios were evaluated which represented situations where a majority of farms shipping to a mill were in relatively close proximity, but some smaller

Table 3.1 Grower distribution scenarios evaluated

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Scenario 1						
Grower numbers	60	-	-	-	-	-
Daily loads	6	-	-	-	-	-
Total daily loads	360	-	-	-	-	-
Scenario 2						
Grower numbers	30	15	-	-	-	-
Daily loads	6	12	-	-	-	-
Total daily loads	180	180	-	-	-	-
Scenario 3						
Grower numbers	24	12	12	-	-	-
Daily loads	6	12	6	-	-	-
Total daily loads	144	144	72	-	-	-
Scenario 4						
Grower numbers	24	12	6	3	-	-
Daily loads	6	12	6	12	-	-
Total daily loads	144	144	36	36	-	-
Scenario 5						
Grower numbers	24	12	4	2	4	-
Daily loads	6	12	6	12	6	-
Total daily loads	144	144	24	24	24	-
Scenario 6						
Grower numbers	24	12	3	2	3	1
Daily loads	6	12	6	12	6	12
Total daily loads	144	144	18	24	18	12

portion of farms were located further away from the mill. It was assumed that 80 percent of the mill daily loads were within 15 minutes travel time to the mill and the remaining 20 percent of daily loads were located 30 or 45 minutes from the mill. Scenario 3 included 24 farms in Group A, 12 farms in Group B, and 12 farms in Group C. Scenario 4 included 24 farms in Group A, 12 farms in Group B, 6 farms in Group C and 3 farms in Group D. Scenario 5 included 24 farms in Group A, 12 farms in Group B, 4 farms in Group C, 2 farms in Group D and 4 farms in Group E. Scenario 6 included 24 farms in Group A, 12 farms in Group B, 3 farms in Group C, 2 farms in Group D, 3 farms in Group E, and 1 farm in Group F. Optimal harvest schedules for all farm groups were determined using the integer linear programming model with the objective of minimizing excessive hourly deliveries throughout the day.

3.4 Optimal Harvest Schedule Results

Linear programming results for each of the six grower distribution scenarios evaluated are presented in this section. Output for each scenario is included in a set of three tables: one specifying optimal harvest schedules for farms included, mill delivery schedules based on the optimal harvest schedules, and a brief summary of the linear programming solution. For scenario 1, optimal harvest schedules for sixty growers included in Group A are shown in Table 3.2. Results show that in order to minimize waiting time at the mill, the number of growers harvest starting times should be 6 growers starting at 6:00 a.m., 11 growers starting at 6:15 a.m., 2 growers starting at 6:30 a.m., 1 grower starting at 8:00 a.m., 7 growers starting at 8:45 a.m., 1 grower starting at 9:30 a.m., 4 growers starting at 10:00 a.m., 8 growers starting at 11:15 a.m., 1 grower starting at 12:00 p.m., 1 grower starting at 1:30 p.m., 11 growers starting at 1:45 p.m., and 7 growers starting at 2:00 p.m.

Table 3.2 Optimal harvest schedules for grower distribution scenario 1

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Grower numbers	60	-	-	-	-	-
Daily loads	6	-	-	-	-	-
Total daily loads	360	-	-	-	-	-
	Optimal sugarcane harvest schedules					
Schedule 1	6 growers 6:00 am 10:30 am	-	-	-	-	-
Schedule 2	11 growers 6:15 am 10:45 am	-	-	-	-	-
Schedule 3	2 grower 6:30 am 11:00 am	-	-	-	-	-
Schedule 9	1 grower 8:00 am 12:30 pm	-	-	-	-	-
Schedule 12	7 growers 8:45 am 1:15 pm	-	-	-	-	-
Schedule 15	1 grower 9:30 am 2:00 pm	-	-	-	-	-
Schedule 17	4 growers 10:00 am 2:30 pm	-	-	-	-	-
Schedule 22	8 growers 11:15 am 3:45 pm	-	-	-	-	-
Schedule 25	1 grower 12:00 pm 4:30 pm	-	-	-	-	-
Schedule 31	1 grower 1:30 pm 6:00 pm	-	-	-	-	-
Schedule 32	11 growers 1:45 pm 6:15 pm	-	-	-	-	-
Schedule 33	7 growers 2:00 am 6:30 pm	-	-	-	-	-

This optimal harvest schedule for scenario 1 spreads mill deliveries out over the day and exceeds the hourly target of 30 truckloads unloading at the mill in only two hours of the day (hours 5 and 10) as shown in Table 3.3. A total of only 9 truckloads over the day are unloaded at the mill in excess of 30 per hour, with 4 loads in hour 5 and 5 loads in hour 10. Linear programming results indicate that it would take 60 trucks to cover all deliveries for scenario 1 (Table 3.4). Shadow prices of the right-hand-sides of constraints specifying the number of farms in each group give an indication of the sensitivity of the objective function value to additional farms in each of the six groups. As shown in Table 3.4, the addition of large farms (Groups B, D or F) would have a greater impact on excessive hourly deliveries than would result from an additional farm in the smaller sized groups (Groups A, C or E).

Linear programming results for scenario 2 are shown in Tables 3.5, 3.6, and 3.7. In this scenario, the 360 daily loads are all within 15 minutes of the mill, but are equally split between small and large farms. Optimal harvest schedule results in Table 3.5 indicate that the group of 15 large farms (twelve loads per day) are split between an early morning harvest start and a later morning harvest start. Starting times for the 30 smaller farms (six loads per day) are scattered across the day with the earliest harvest schedule starting at 6:15 a.m. and the latest harvest schedule starting at 1:45 p.m. The target of 30 trucks per hour unloading at the mill is exceeded only twice, with 7 trucks in hour 5 and 8 trucks in hour 10 (Table 3.6). A total of 60 trucks would be required to cover all deliveries in scenario 2 (Table 3.7). Similar to scenario 1, the shadow prices of the right-hand-sides of constraints specifying farm numbers indicated that additional farms with 12 loads per day would have a greater impact on excessive trucks arriving at the mill in a given hour than would additional farms with only 6 loads per day.

Table 3.3 Mill delivery schedule results for grower distribution scenario 1

	Sugarcane grower groups						
	Group A	Group B	Group C	Group D	Group E	Group F	Total
Grower numbers	60	-	-	-	-	-	60
Daily loads	6	-	-	-	-	-	-
Total daily loads	360	-	-	-	-	-	360
Hour	Daily loads unloading at the mill						
1	-	-	-	-	-	-	-
2	25	-	-	-	-	-	25
3	30	-	-	-	-	-	30
4	30	-	-	-	-	-	30
5	34	-	-	-	-	-	34
6	30	-	-	-	-	-	30
7	30	-	-	-	-	-	30
8	30	-	-	-	-	-	30
9	30	-	-	-	-	-	30
10	35	-	-	-	-	-	35
11	30	-	-	-	-	-	30
12	30	-	-	-	-	-	30
13	26	-	-	-	-	-	26
14	-	-	-	-	-	-	-
Total	360	-	-	-	-	-	360

Table 3.4 Linear program solution summary for grower distribution scenario 1

Optimal objective function value
= 9 total loads per day exceeding minimum hourly goal

Minimum total number of trucks required to cover all deliveries
= 60 trucks

Impact of additional new farms shipping to mill on excess hourly deliveries

Farm group	RHS shadow price
A	3.00
B	5.50
C	1.33
D	5.00
E	0.75
F	4.00

Table 3.5 Optimal harvest schedules for grower distribution scenario 2

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Grower numbers	30	15	-	-	-	-
Daily loads	6	12	-	-	-	-
Total daily loads	180	180	-	-	-	-
	Optimal sugarcane harvest schedules					
Schedule 1	-	7 growers 6:00 am 3:00 pm	-	-	-	-
Schedule 2	7 growers 6:15 am 10:45 am	-	-	-	-	-
Schedule 3	1 grower 6:30 am 11:00 am	-	-	-	-	-
Schedule 6	7 growers 7:15 am 11:45 am	-	-	-	-	-
Schedule 15	-	8 growers 9:30 am 6:30 pm	-	-	-	-
Schedule 25	1 grower 12:00 pm 4:30 pm	-	-	-	-	-
Schedule 28	6 growers 12:45 am 5:15 pm	-	-	-	-	-
Schedule 32	8 growers 1:45 pm 6:15 pm	-	-	-	-	-

Table 3.6 Mill delivery schedule results for grower distribution scenario 2

	Sugarcane grower groups						
	Group A	Group B	Group C	Group D	Group E	Group F	Total
Grower numbers	30	15	-	-	-	-	45
Daily loads	6	12	-	-	-	-	-
Total daily loads	180	180	-	-	-	-	360
Hour	Daily loads unloading at the mill						
1	-	-	-	-	-	-	-
2	8	14	-	-	-	-	22
3	22	7	-	-	-	-	29
4	23	7	-	-	-	-	30
5	15	22	-	-	-	-	37
6	15	15	-	-	-	-	30
7	7	23	-	-	-	-	30
8	8	22	-	-	-	-	30
9	15	15	-	-	-	-	30
10	15	23	-	-	-	-	38
11	22	8	-	-	-	-	30
12	22	8	-	-	-	-	30
13	8	16	-	-	-	-	24
14	-	-	-	-	-	-	-
Total	180	180	-	-	-	-	360

Table 3.7 Linear program solution summary for grower distribution scenario 2

Optimal objective function value
= 15 total loads per day exceeding minimum hourly goal

Minimum total number of trucks required to cover all deliveries
= 60 trucks

Impact of additional new farms shipping to mill on excess hourly deliveries

Farm group	RHS shadow price
A	1.50
B	4.00
C	1.00
D	3.00
E	0.50
F	3.00

Results for scenario 3 are shown in Tables 3.8, 3.9, and 3.10. This scenario has 80 percent of the farms located within 15 minutes from the mill (Groups A and B) and 20 percent of the farms (72 daily loads) located 30 minutes from the mill on relative small farms (six loads per day). Starting harvest times for farms in Group A range from 6:15 a.m. to 1:45 p.m. (Table 3.8). Larger farms, in Group B, start harvest at 6:00 a.m. and 6:15 a.m. The twelve farms in Group C have 4 farms starting harvest at 6:00 a.m. and the remaining 8 farms start harvest at 2:00 p.m. Excessive trucks unloading at the mill again occur at hours 5 and 10, with four trucks in excess of 30 unloading at the mill in those time periods (Table 3.9). A total of 68 trucks would be required to cover all harvest and delivery schedules determined by the linear programming solution. Additions of larger farms to the scenario would have a larger impact on excessive hourly truck deliveries (3.17 to 4.00) than would the addition of smaller farms (1.33 to 1.67).

Scenario 4 is similar to scenario 3 in that 20 percent of the daily loads delivered to the mill are 30 minutes from the mill, except that half of these distant loads are from larger farms (twelve loads per day). Optimal harvest schedules for scenario 4 are similar to scenario 3 with starting times for Group A farms spread across the day and starting times from Group B farms occurring in the early morning hours (Table 3.11). The six farms in Group C would start harvest at 2:00 p.m. and the three larger farms in Group D would start at 9:30 a.m. Although the same number of trucks would be required to cover all harvest schedules in scenario 4 (68 trucks), the total number of excessive hourly deliveries increased by one to nine per day (Table 3.13). The fifth and tenth delivery hours remain the critical ones, with one excessive hourly delivery in hour 5 and eight excessive hourly deliveries in hour 10 (Table 3.12).

Scenarios 5 and 6 represent situations where mills are receiving harvested sugarcane from longer distances. In both scenarios, 80 percent of the daily loads are within 15 minutes of the

Table 3.8 Optimal harvest schedules for grower distribution scenario 3

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Grower numbers	24	12	12	-	-	-
Daily loads	6	12	6	-	-	-
Total daily loads	144	144	72	-	-	-
	Optimal sugarcane harvest schedules					
Schedule 1	-	8 growers 6:00 am 3:00 pm	4 growers 6:00 am 10:30 am	-	-	-
Schedule 2	3 growers 6:15 am 10:45 am	4 growers 6:15 am 3:15 pm	-	-	-	-
Schedule 9	4 growers 8:00 am 12:30 pm	-	-	-	-	-
Schedule 12	3 growers 8:45 am 1:15 pm	-	-	-	-	-
Schedule 22	3 growers 11:15 am 3:45 pm	-	-	-	-	-
Schedule 32	11 growers 1:45 pm 6:15 pm	-	-	-	-	-
Schedule 33	-		8 growers 2:00 pm 6:30 pm			

Table 3.9 Mill delivery schedule results for grower distribution scenario 3

	Sugarcane grower groups						
	Group A	Group B	Group C	Group D	Group E	Group F	Total
Grower numbers	24	12	12	-	-	-	48
Daily loads	6	12	6	-	-	-	-
Total daily loads	144	144	72	-	-	-	360
Hour	Daily loads unloading at the mill						
1	-	-	-	-	-	-	-
2	3	20	4	-	-	-	27
3	6	16	8	-	-	-	30
4	14	12	4	-	-	-	30
5	10	20	4	-	-	-	34
6	10	16	4	-	-	-	30
7	17	12	-	-	-	-	29
8	9	20	-	-	-	-	29
9	14	16	-	-	-	-	30
10	14	12	8	-	-	-	34
11	14	-	16	-	-	-	30
12	22	-	8	-	-	-	30
13	11	-	8	-	-	-	19
14	-	-	8	-	-	-	8
Total	144	144	72	-	-	-	360

Table 3.10 Linear program solution summary for grower distribution scenario 3

Optimal objective function value
= 8 total loads per day exceeding minimum hourly goal

Minimum total number of trucks required to cover all deliveries
= 68 trucks

Impact of additional new farms shipping to mill on excess hourly deliveries

Farm group	RHS shadow price
A	1.67
B	4.00
C	1.67
D	3.17
E	1.33
F	3.33

Table 3.11 Optimal harvest schedules for grower distribution scenario 4

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Grower numbers	24	12	6	3	-	-
Daily loads	6	12	6	12	-	-
Total daily loads	144	144	36	36	-	-
	Optimal sugarcane harvest schedules					
Schedule 1	-	4 growers 6:00 am 3:00 pm	-	-	-	-
Schedule 2	7 growers 6:15 am 10:45 am	3 growers 6:15 am 3:15 pm	-	-	-	-
Schedule 3	1 grower 6:30 am 11:00 am	5 growers 6:30 am 3:30 pm	-	-	-	-
Schedule 12	4 growers 8:45 am 1:15 pm	-	-	-	-	-
Schedule 15	-	-	-	3 growers 9:30 am 6:30 pm	-	-
Schedule 22	2 growers 11:15 am 3:45 pm	-	-	-	-	-
Schedule 32	10 growers 1:45 pm 6:15 pm	-	-	-	-	-
Schedule 33	-	-	6 growers 2:00 pm 6:30 pm	-	-	-

Table 3.12 Mill delivery schedule results for grower distribution scenario 4

	Sugarcane grower groups						
	Group A	Group B	Group C	Group D	Group E	Group F	Total
Grower numbers	24	12	6	3	-	-	45
Daily loads	6	12	6	12	-	-	-
Total daily loads	144	144	36	36	-	-	360
Hour	Daily loads unloading at the mill						
1	-	-	-	-	-	-	-
2	8	16	-	-	-	-	14
3	15	15	-	-	-	-	30
4	13	17	-	-	-	-	30
5	12	16	-	3	-	-	31
6	12	15	-	3	-	-	30
7	10	17	-	3	-	-	30
8	8	16	-	6	-	-	30
9	12	15	-	3	-	-	30
10	12	17	6	3	-	-	38
11	12	-	12	6	-	-	30
12	20	-	6	3	-	-	29
13	10	-	6	3	-	-	19
14	-	-	6	3	-	-	9
Total	144	144	36	36	-	-	360

Table 3.13 Linear program solution summary for grower distribution scenario 4

Optimal objective function value
= 9 total loads per day exceeding minimum hourly goal

Minimum total number of trucks required to cover all deliveries
= 68 trucks

Impact of additional new farms shipping to mill on excess hourly deliveries

Farm group	RHS shadow price
A	1.67
B	4.00
C	1.67
D	3.67
E	0.67
F	3.33

mill and the remaining 20 percent are 30 and 45 minutes from the mill. Scenario 5 represents the situation where the farms furthest from the mill are all small farms. Scenario 6 represents the situation where the farms furthest from the mill also contain larger sized farms. Optimal harvest schedule results for scenario 5 are shown in Tables 3.14, 3.15 and 3.16. A total of 70 trucks were required to cover the optimal harvest schedules with a total of eight loads exceeding the hourly target of 30. Optimal harvest schedule results for scenario 6 are shown in Tables 3.17, 3.18 and 3.19. A total of 69 trucks were required to cover the optimal harvest schedules with a total of nine loads exceeding the hourly target of 30. Once again the fifth and tenth hour of delivery appeared to be the most critical in terms of excessive hourly deliveries.

Table 3.14 Optimal harvest schedules for grower distribution scenario 5

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Grower numbers	24	12	4	2	4	-
Daily loads	6	12	6	12	6	-
Total daily loads	144	144	24	24	24	-
	Optimal sugarcane harvest schedules					
Schedule 1	-	7 growers 6:00 am 3:00 pm	-	-	-	-
Schedule 2	6 growers 6:15 am 10:45 am	4 growers 6:15 am 3:15 pm	-	-	-	-
Schedule 3	-	1 grower 6:30 am 3:30 pm	-	-	-	-
Schedule 9	5 growers 8:00 am 12:30 pm	-	-	-	-	-
Schedule 12	1 grower 8:45 am 1:15 pm	-	-	-	-	-
Schedule 15	-	-	-	2 growers 9:30 am 6:30 pm	-	-
Schedule 22	3 growers 11:15 am 3:45 pm	-	-	-	-	-
Schedule 31	2 growers 1:30 pm 6:00 pm	-	-	-	-	-
Schedule 32	-	-	-	-	-	-
Schedule 33	7 growers 2:00 pm 6:30 pm	-	4 growers 2:00 pm 6:30 pm	-	4 growers 2:00 pm 6:30 pm	-

Table 3.15 Mill delivery schedule results for grower distribution scenario 5

	Sugarcane grower groups						
	Group A	Group B	Group C	Group D	Group E	Group F	Total
Grower numbers	24	12	4	2	4	-	46
Daily loads	6	12	6	12	6	-	-
Total daily loads	144	144	24	24	24	-	360
Hour	Daily loads unloading at the mill						
1	-	-	-	-	-	-	-
2	6	19	-	-	-	-	26
3	12	16	-	-	-	-	28
4	17	13	-	-	-	-	30
5	12	19	-	2	-	-	34
6	12	16	-	2	-	-	30
7	15	13	-	2	-	-	29
8	7	19	-	4	-	-	30
9	12	16	-	2	-	-	30
10	12	13	4	2	4	-	34
11	14	-	8	4	4	-	30
12	16	-	4	2	8	-	30
13	9	-	4	2	4	-	19
14	-	-	4	2	4	-	10
Total	144	144	24	24	24	-	360

Table 3.16 Linear program solution summary for grower distribution scenario 5

Optimal objective function value
= 8 total loads per day exceeding minimum hourly goal

Minimum total number of trucks required to cover all deliveries
= 70 trucks

Impact of additional new farms shipping to mill on excess hourly deliveries

Farm group	RHS shadow price
A	1.50
B	4.00
C	1.00
D	3.00
E	1.00
F	3.00

Table 3.17 Optimal harvest schedules for grower distribution scenario 6

	Sugarcane grower groups					
	Group A	Group B	Group C	Group D	Group E	Group F
Grower numbers	24	12	3	2	3	1
Daily loads	6	12	6	12	6	12
Total daily loads	144	144	18	24	18	12
	Optimal sugarcane harvest schedules					
Schedule 1	-	4 growers 6:00 am 3:00 pm	-	-	-	-
Schedule 2	9 growers 6:15 am 10:45 am	2 growers 6:15 am 3:15 pm	-	-	-	-
Schedule 3	-	4 growers 6:30 am 3:30 pm	-	-	-	-
Schedule 9	3 growers 8:00 am 12:30 pm	-	-	-	-	-
Schedule 15	-	2 growers 9:30 am 6:30 pm	-	2 growers 9:30 am 6:30 pm	-	1 grower 9:30 am 6:30 pm
Schedule 22	3 growers 11:15 am 3:45 pm	-	-	-	-	-
Schedule 25	1 grower 12:00 pm 4:30 pm	-	-	-	-	-
Schedule 31	1 grower 1:30 pm 6:00 pm	-	-	-	-	-
Schedule 32	7 growers 1:45 pm 6:15 pm	-	-	-	-	-
Schedule 33	-	-	3 growers 2:00 pm 6:30 pm	-	3 growers 2:00 pm 6:30 pm	-

Table 3.18 Mill delivery schedule results for grower distribution scenario 6

	Sugarcane grower groups						
	Group A	Group B	Group C	Group D	Group E	Group F	Total
Grower numbers	24	12	3	2	3	1	45
Daily loads	6	12	6	12	6	12	-
Total daily loads	144	144	18	24	18	12	360
Hour	Daily loads unloading at the mill						
1	-	-	-	-	-	-	-
2	9	14	-	-	-	-	23
3	18	12	-	-	-	-	30
4	15	14	-	-	-	-	29
5	12	16	-	2	-	-	30
6	12	14	-	2	-	2	30
7	9	18	-	2	-	1	30
8	8	16	-	4	-	1	29
9	12	14	-	2	-	2	30
10	12	18	3	2	3	1	39
11	14	2	6	4	3	1	28
12	15	2	3	2	6	2	30
13	8	4	3	2	3	1	21
14	-	-	3	2	3	1	9
Total	144	144	18	24	18	12	360

Table 3.19 Linear program solution summary for grower distribution scenario 6

Optimal objective function value
= 9 total loads per day exceeding minimum hourly goal

Minimum total number of trucks required to cover all deliveries
= 69 trucks

Impact of additional new farms shipping to mill on excess hourly deliveries

Farm group	RHS shadow price
A	1.50
B	4.00
C	1.00
D	3.00
E	1.00
F	3.00

CHAPTER 4. SUMMARY AND CONCLUSIONS

4.1 Summary of Research Problem

Sugarcane production is a major agricultural enterprise in Louisiana. Rising production costs, primarily associated with increase fuel and fertilizer prices, combined with a relatively flat to slightly declining market price trend have significantly reduced profit margins from sugarcane production in the state over the past few years. Sugarcane growers have been searching for ways to reduce production costs as a means of improving net returns. Although several different areas of production have been considered, harvest operations is one area in which growers can have considerable influence on costs per unit.

The harvest of sugarcane in Louisiana represents a major cost item in the production of crop in the state. Estimation of current sugarcane harvest costs as well as economic evaluation of the impact of various factors on the performance and cost of this production phase are important to growers in conduction these harvest operations as efficient and cost effective as possible. As unloading time at the mill is a primary factor influencing the efficiency of harvest operations on the farm, developing harvest schedules for groups of farms to minimize waiting time at the mill is important for efficient and cost effective operations at both the farm and mill.

The general objective of this research project was to estimate the current fixed and variable costs of harvesting sugarcane in Louisiana with combine harvest units and to determine optimal harvest schedules for groups of farms delivering sugarcane to a common mill.

The specific objectives of this research project were: (1) to survey of a representative sample of sugarcane growers in Louisiana to collect data on factors influencing sugarcane harvest cost; (2) to estimate the current fixed and variable costs associated with harvesting sugarcane in Louisiana with a single combine harvester and complement of wagons and to perform sensitivity analysis of truck waiting time as it affects harvest cost; and (3) to determine optimal harvest scheduling for a group of farms delivering harvested sugarcane to a common mill with the goal of minimizing waiting time at the mill.

4.2 Summary of Research Results

Data were collected from a sample of sugarcane growers who shipped harvested sugarcane to Cora-Texas sugar factory for processing during the 2004 harvest season. This survey was conducted by mail during the summer of 2005. Information obtained by the survey included farm size, a description of harvest equipment used as well as related data on actual harvest operations during the 2004 harvest season.

Based on survey respondent data, the average area harvested for sugar per farm in 2004 was 1,530.4 acres, producing an average total production of 45,284.9 tons of sugarcane. Farms were relatively evenly split between requiring one and two combine harvesters to harvest their crop. The average number of combines used by respondents was 1.6 per farm along with an average of 4.7 wagons used to transfer harvested sugarcane from field to truck. With a mean daily quota of 612.0 tons per day to be harvested and delivered to the mill, harvesting operations by the growers surveyed averaged 20.0 acres harvested per day at a harvesting rate of 45.0 tons per hour. Using 2004 input prices, average estimated harvest costs were calculated to be $2.41 per ton for fixed expenses, $2.79 per ton for variable expenses, resulting in a total harvest cost of $5.20 per ton.

A cost analysis was conducted to evaluate the impact of increased truck waiting time at the mill on farm level harvest costs. Increased truck waiting time at the mill causes harvest operations at the farm to cease and wait until an unloaded truck arrives at the farm for loading. This waiting time influences the fuel and labor costs of the harvest and tractors being used in the harvest operations. The cost analysis conducted found that for every one minute of waiting time at the farm during harvest operations, the total harvest fuel and labor costs were increased by approximately $1.30 per acre.

The most direct way to reduce waiting time of harvest operations at the farm level is to schedule harvest starting times of all farms shipping to a particular mill, thereby minimizing the waiting time of trucks delivering harvested sugarcane to the mill during any time period of the day. An integer linear programming model was developed which simulated the daily delivery of approximately 10,000 tons of harvested sugarcane with the goal of scheduling harvest operations of all farms to better coordinate trucking operations.

The linear programming model simulated daily delivery of 360 truck loads of harvested sugarcane from two different sizes of farms at various distances from the mill. Six different grower size and location scenarios were simulated representing typical harvest and delivery situations faced by mills in the state. The linear programming model performed well in determining specific harvest schedules for each combination of farms included in the analysis as well as determining the minimum number of trucks required to cover all harvest schedules.

Simulation of approximately 10,000 tons of harvested sugarcane delivered from farms within 15 minutes travel time from the mill indicated that approximately 60 trucks would be required to cover all deliveries. With approximately 20 percent of the daily mill deliveries coming from farms 30 to 45 minutes from the mill, the required number of trucks increases by 8 to 10 per day. Harvest and delivery schedules for smaller farms could be easily distributed throughout the day. Less flexibility was available to optimize harvest schedules for larger farms given the expanded time required to harvest a daily quota of sugarcane. Results of the analysis of the six scenarios demonstrated that transport operations between farm and mill, which impacts harvest operation efficiency, could be improved with better coordination of harvest operations across all farms.

4.3 Conclusions and Areas of Future Research

A couple of major conclusions can be drawn from the research conducted for this project. First, harvest costs are a major component of total farm production costs of sugarcane farms in Louisiana and that efficient harvest operations, both in terms of equipment use and acreage used over, can significantly impact harvest costs per acre. Secondly, waiting time can have a substantial impact on harvest costs and this impact can be minimized but would require coordination across a large group of farms in better scheduling of harvest operations.

Future areas of research related to this project would include the actual implementation of the type of mill-wide harvest schedules developed in this research. Data could be collected on current harvest and delivery operations to a specific mill and then evaluate the impact of implementing a coordinated harvest schedule for all farms delivering to that particular mill. Cost efficiencies and savings could be evaluated at both the farm and mill level.

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APPENDIX A. PRODUCER SURVEY

CORA-TEXAS PRODUCER SURVERY
2004 HARVESTING COSTS

The purpose of this survey is to estimate an average sugarcane harvest cost for the 2004 crop for growers at Cora-Texas. Average sugarcane harvest costs developed from this survey will be used in evaluating the potential for group harvesting at Cora-Texas.

PRODUCER - ____________________

(1) Sugarcane Harvesting Equipment

This section collects information on harvesting equipment used during the 2004 harvest. Information on combines and wagons, collected by Cora-Texas are indicated. Please indicate purchase price and anticipated total years of use for each item and make any corrections as needed.

Combines:	Make	Model	Year Purchased	Purchase Price	Anticipated Years of Use	Hours of Use in 2004
(a.)				$		
(b.)				$		
(c.)				$		
(d.)				$		

Wagons:	Make	Size (tons)	Number of Wagons	Year Purchased	Purchase Price (each)	Anticipated Years of Use
(a.)					$	
(b.)					$	
(c.)					$	
(d.)					$	
(e.)					$	

(2) Estimated Daily Harvesting Hours for 2004

This section collects information on the number of hours required to harvest sugarcane. Please provide your best estimate of the following information for a typical day of harvest during the 2004 harvest season. If you were a split-shipper, provide information for all sugarcane harvested per day. Hours in field includes time spent actually cutting as well as time spent waiting for trucks. Provide your best estimate of the average cutting rate per combine in tons per hour.

(a.) Daily quota = ________ tons

(b.) 2004 yield = _________ tons/acre

(c.) Harvested per day =________ acres

(d.) Hours in field per day = ________ hours

(e.) Hours actually cutting = ________ hours

(f.) Cutting rate = __________ tons per hour

(3) Harvest Fuel and Labor for 2004

This section collects information on fuel and labor required to harvest sugarcane in 2004. Please provide your best estimate of the following information for a typical day of harvest during the 2004 harvest season, as in question 2 above. If you were a split-shipper, provide information for all sugarcane harvested per day.

For a typical day of harvest during the 2004 harvest season:

Number of Combines Used	Number of Combine Drivers	Base Hourly Wage ($ / hour)	Combine Fuel Consumption (gallons / hour)
(a.)______________	________________	____________	___________

Number of Wagons Used	Number of Tractor Drivers	Base Hourly Wage ($ / hour)	Tractor Fuel Consumption (gallons / hour)
(b.)______________	________________	____________	____________

(4) Tractors Used During Harvest in 2004

This section collects information on tractors used to pull wagons to harvest sugarcane in 2004. Please provide your best estimate of the total hours of use as well as the portion of hours used during harvest. If you were a split-shipper, provide information on tractors used for all sugarcane harvested.

Total number of tractors used during the 2004 harvest season = _______________

Provide the following information for up to 3 tractors used with wagons during the 2004 harvest season.

	Make/Model	Size (hp)	Year Purchased	Useful Life (years)	Total Hours For All Uses in 2004 (total hours)	Total Hours of Harvest Use in 2004 (harvest hours)
(a.)	__________	_______	________	______	__________	__________
(b.)	__________	_______	________	______	__________	__________
(c.)	__________	_______	________	______	__________	__________

(5) Actual Harvest Costs for 2004

This section collects information on your actual harvest costs for the 2004 season as a whole. Please indicate the total acres harvested and total tons harvested over the 2004 season. Please indicate your best estimate of the total harvest costs for the entire harvest over the acres indicated. If you were a split-shipper, provide information for all sugarcane harvested during the 2004 season.

Total Acres Harvested in 2004 = __________________ acres

Total Tons Harvested in 2004 = ___________________ tons

(Please check all appropriate)
This harvest cost includes:

[ ] Fuel
[ ] Labor
[ ] Repairs
[ ] Other (list)
____
____
____

Total Harvest Cost	Cost per Ton
$_______________	$____________

VITA

Francis Gil Barker was born in New Orleans, Louisiana, in 1952 and was raised on Valentine Sugars Plantation near Lockport, Louisiana. He attended Holy Savior High School in Lockport and graduated in 1970. From 1970 to 1972, he attended Louisiana State University. He joined the Louisiana Army National Guard in 1972. He married the former Rebecca Padgett in 1973 and they have four sons, Beau, Brandon, Travis and D.J. In 1976, he completed a Bachelor of Science degree in plant science from Nicholls State University. He worked in the Louisiana sugar industry from 1976 to 1982, when he began working for the L.S.U. Agricultural Center at the Red River Research Station in Bossier City, Louisiana. In 1985, he transferred to the L.S.U. Department of Plant Pathology and Crop Physiology and completed a Master of Science degree in plant health in 1991. After working as an area agricultural agent in Northwest Louisiana, he moved to Baton Rouge to oversee the L.S.U. veterinary science farm while completing a Master of Science degree in agricultural economics.