Multi-objective Optimization for Cost Reduction of Mechanical Sugarcane Harvesting and Transportation in Thailand

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Notations

AOS	the amount of sugarcane, t
ASE	the average travel speed of an empty truck, km/h
ASF	the average travel speed of a loaded truck, km/h
BDT	the required time spent on refueling of the truck per round trip, min
COT	the loading capacity of the truck, t
CSP	the average cutting speed of the mechanical harvester, m/min
CT	the chopper's cutting time in a day, min
DAY_i	the number of operating days of a harvester on the field i, d
DIS_i	the distance from the field i to the factory, km
DMF	the distance from the field to the sugar factory, km
DPT	the driver's personal time per truck per round trip, min
DT	the time involved in deterioration of the harvests, min
FS	the field size, ha
h	the number of mechanical harvesters, unit
LC_i	the capacity of a trailer worked with a harvester operating on the field i, t
LD_i	the amount of delivered sugarcane per day of a trailer worked with the harvester operating on the field i, t
LDT_i	the deterioration time of sugarcane transported by a trailer worked with a harvester operating on the field i, min
LT_i	the number of 10-wheeled trucks with trailers worked with a harvester operating on the field i, unit
$LTRIP_i$	the number of round trips per day of the trailer worked with a harvester operating on the field i

NTRUCK	the number of trucks required for working with a mechanical harvester without the pause time of the harvester waiting for a truck, unit
RL	the row length of the field, m
RS	the row spacing of the crop which is set equal to 1.5 m
RTRIP	the number of round trips per day that a truck makes
SC_i	the capacity of a 10-wheeled truck worked with a harvester operating on the field i, t
SD_i	the amount of delivered sugarcane per day of a 10-wheeled truck working with a harvester operating on the field i, t
SDT_i	the deterioration time of the sugarcane transported by a 10-wheeled truck worked with a harvester operating on the field i, min
ST_i	the number of 10-wheeled trucks working with a harvester operating on the field i, unit
$STRIP_i$	the number of round trips per day of a 10-wheeled truck worked with a harvester operating on field i
TAD	the time for adjustment of the harvested sugarcane in the truck, min
TBACK	the return trip time of the truck from the sugar factory to the field, min
TFACT	the time consumed by the truck at the sugar factory, min
TGO	the time to deliver the harvest from the field to the sugar factory, min
TLT	the loading time for a truck, min
TRO	the time for inspecting and unloading operations at a sugar factory, min
TTC	the required time for the change of a truck, s
TTT	the turning time of a harvester and a truck at the head land, min
WTM	the waiting time of a truck in queue at a sugar factory, min
Y_i	the specific yield of the field i, t

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Chapter 1

Introduction

1.1 Background of the research

Sugarcane is a crucial economic crop of Thailand. It is a perennial crop grown mainly as a source of sugar. The procedure for processing sugar involves harvesting the sugarcane stalks, then shredding them and extracting the sugarcane juice. Raw sugar is produced from the juice and is later refined into white sugar.

Thailand is one of the world's major sugar producers, producing on average more than five million t per year. The sugarcane harvesting and transportation is a huge logistical operation in which the amount of 47 to 64 million t of sugarcane must be cut and transported every year. This operation requires thousands of workers, dozens of cutting machines, numerous numbers of tractors, trucks and trailers all over the country. However, the cost of harvesting and transportation occupies a large portion of total production cost. Nearly half of the total cost is consumed to harvesting and transportation. Ultimately, both harvesting and transportation costs are regarded as determinant factors of sugar’s domestic consumer price and international export value.

The high cost of sugarcane harvesting and transportation is one of the reasons for the reduction in the total amount of Thailand’s sugarcane cultivation. Farmers who own small fields and/or whose fields are located far from a sugar factory tend to abandon sugarcane cultivation. Such farmers have changed their cultivation from sugarcane to other crops that lead lower production costs, such as cassava. These facts suggest the necessity for further reduction of harvesting and transportation costs. In addition, improper harvesting and/or delay in transportation will result in the crop’s deterioration which leads to a decrease for the farmer's income and also a reduction in the amount of sugar produced. This fact implies that efficiencies of harvesting and transportation directly influence the income of sugarcane farmers and sugar factories.

Therefore, more effective cost reduction and efficiency improvement in sugarcane harvesting and transportation are needed in order to maintain its current status in a rigorously competitive international sugar market. It is necessary to comprehend the harvesting and transportation processes, and their current drawbacks adequately in order to reduce the total production cost and improve the efficiency in sugarcane harvesting and transportation system. One objective of this study is to clarify the current technical shortcomings of the harvesting and transportation processes.

As presented in Chapter 3, the study revealed that there is the possibility of the use of mechanical harvesting to reduce the cost of sugarcane harvesting. The efficiency of the mechanical harvesting system could be improved by increasing the number of trucks used. However, an increase of the number of trucks was not an effective solution when the improvement in the efficiency of the sugarcane harvesting and transportation system as a whole was considered. The ways and manners on maximum utilization in relation to availability of trucks in the study area are of utmost concern. Proper determination of the optimum truck number is needed for the management of sugarcane production. Thus, the effective allocation of trucks has been discussed as a significant issue for improving the efficiency of the sugarcane harvesting and transportation system.

However, its truck allocation is complicated by the facts that field size of sugarcane cultivation in Thailand is in general small and the ownership structure of the Thai sugar industry is specific. There are three groups involved in the harvesting and transportation processes: sugarcane farmers, the owners of mechanized resources, and the sugar factories. There are individual needs of each participant in the chain concerning their quests for further efficiency. None of the previous studies considered compromise planning in this kind of environment for mechanized resources allocation in sugarcane harvesting and transportation. Therefore, truck allocation for improving mechanical harvesting and transportation system in Thailand considered together with input from the groups involved has been studied through the usage of multi-objective optimization. Both efficiency and the appropriate distribution of profit were considered through multi-objective planning reflecting the desires of the three groups involved, as presented in Chapter 4.

1.2 Objectives

This research was done in an effort to reduce the cost of harvesting and transportation process that occupied a significant portion of Thailand's sugarcane's total production cost. Also, this research was done in an attempt to improve the efficiency in sugarcane harvesting and transportation system in Thailand. To achieve these goals, a field survey, interviews, and time studies on harvesting and transportation operations were conducted in northeastern Thailand. Models simulating the mechanical sugarcane harvesting and transportation system in Thailand were developed. Analyses through the use of a simple sugarcane harvesting and transportation simulation were performed. Three objective functions for truck allocation were defined based on integer programming. As well, computational experiment was performed to check the performance of multi-objective optimization for truck allocation. These have been carried out with the following objectives:

1. To clarify the current shortcomings of the sugarcane harvesting and transportation processes in Thailand.

2. To gain insights into the relations between the mechanical harvesting and transportation processes.

3. To examine the possibility of further mechanization and its effect on the profitability of sugarcane harvesting and transportation.

4. To develop truck allocation plans to reduce the operating cost and improve the efficiency of mechanical sugarcane harvesting and transportation in Thailand, reflecting the considerations of the three groups involved: the owners of mechanical harvesters and trucks, sugarcane farmers, and sugar factories.

5. To demonstrate the possibility to distribute the profit of each group engaged in sugarcane harvesting and transportation processes, as well as, to clarify the factors affecting the cost of them.

1.3 Outline of the research

This dissertation is organized as follows: In Chapter 2, description of the Thai sugarcane and sugar industry is provided. The previous researches related to sugarcane mechanization, as well as simulation and optimization for supply chain management of the sugar industry are briefly reviewed. In Chapter 3, mechanization for the improvement of the sugarcane harvesting and transportation system in Thailand is presented. The results obtained from a case study in Udon Thani province, northeastern Thailand, are described. In Chapter 4, truck allocation planning for cost reduction of mechanical sugarcane harvesting in Thailand is explained. The usage of multi-objective optimization given more proper allocation of mechanized resources to sugarcane fields is demonstrated. Also, the achievement in cost reduction and efficiency improvement in mechanical sugarcane harvesting is described in this chapter. Finally, some conclusions and recommendations are given in Chapter 5.

Chapter 2

Literature review

2.1 Sugarcane and sugar industry in Thailand

2.1.1 Role of sugarcane and sugar industry in Thailand

The sugarcane and sugar industry plays an important role in Thailand, both as a basic product supplier and a source of employment. This industry is one of the country's main industrial sectors. Since Thailand produces sugar as an export commodity, this income can be regarded as source of foreign currency which is to contribute to support its industrial development. This industry can generate revenue to the local economy by exceeding 1,316 million US$ or 50,000 million baht annually through exports and domestic sales of sugar (1 US$ equals to 38 baht). Also, it can employ more than 1,000,000 sugarcane farmers and other people in related sectors (Cane and Sugar Industry Policy Bureau, 2006).

2.1.2 Thailand's sugarcane and sugar production

Thailand's sugarcane and sugar industry has been grown continually. Now it becomes one of the world's largest sugar exporters. However, during the past three years, or 2003-2006, the amount of sugarcane and sugar production has decreased because other crops such as cassava, palm oil, and rubber trees offered to be more profitable. Sugarcane farmers have changed their crops into other crops that necessitate less production costs.

In period of 2006 to 2007, its sugarcane and sugar production has recovered due to high market price of sugarcane in the crop year of 2005 to 2006. The volume of sugarcane increased to 63.80 million t, and total amount of produced sugar in period of 2006 to 2007 amounted 6.72 million t. The amount of sugar exported in 2006 to 2007 is estimated at 4.72 million t which were 2.19 million t comparatively in 2005 to 2006 (Office of the Cane and Sugar Board, 2007). However, these volumes are lower than the figures of 2002 to 2003 (Table 2.1).

Table 2.1 Amounts of sugarcane and sugar production, consumption, and export in the crop year of 2001 to 2007

Crop year	Amount of sugarcane production, million t	Amount of produced sugar, million t	Domestic consumption, million t	Export, million t
2001 to 2002	59.50	6.14	1.81	4.01
2002 to 2003	74.07	7.28	1.94	5.18
2003 to 2004	64.48	7.01	2.13	4.66
2004 to 2005	47.82	5.17	2.20	3.02
2005 to 2006	46.69	4.67	2.28	2.19
2006 to 2007	63.80	6.72	2.00	4.72

In the crop year 2006 to 2007, Thai sugar production is projected higher than the previous year about 38%. However, the value of Thai sugar export in 2007 is estimated to be slightly increased over the last year due to decline of sugar price in world market in 2007. The sugar price trend in world market has been downwards in 2007 due to increase in cultivation area of the world’s major sugar producers. Brazil is forecast to produce 31.6 million t of sugar, up 18% from a year earlier, for instance.

2.1.3 Thai sugar factory

The sugar factory is usually located geographically close to the sugarcane fields. At present there are 46 sugar factories in Thailand situated in four different parts of the country. There are 9, 17, 5, and 15 sugar factories in the Northern, Central, Eastern, and Northeastern regions, respectively (Office of the Cane and Sugar Board, 2006). The milling season for each year starts from November and ends in May influenced by the quantity of sugar cane supplied to the sugar factory.

All sugar factories are requested to report their milling capacities in terms of quantity of sugarcane supplied to factory per day to the Office of the Cane and Sugar Board (OCSB), the Ministry of Industry. One of large-scale factories is the Kaset Thai which embraces production capacity of 40,000 t of sugarcane per day, while the smallest one is the Uttaradit with production capacity of 2,683 t of sugarcane per day.

Three kinds of processed sugar are available in the market as described below:

(1) Raw sugar for export mainly recovered by defecation method

(2) White sugar for local consumption mainly provided by carbonation method

(3) Refined sugar for domestic consumption and export mainly produced by carbonation, and ion exchange resin and activated carbon method

The excess amount of sugar extracted from domestic consumption is prepared for export through seven exporting companies. Each sugar factory are ready to export certain amount of refined sugar along with the quota.

2.2 Utilization of sugarcane

Since sugarcane is highly efficient converter of solar energy, it gives the highest annual yield of biomass. It has the highest energy-to-volume ratio among energy crops. Approximately, one ton of sugarcane biomass (based on bagasse, foliage, and ethanol output) has an energy content equivalent to one barrel of crude oil (ISO, 2004). Thus, the sugar industry does not focus solely on the sugar production as its main objective. Instead, it endeavors to become a high efficiency agro industry with widespread by-product diversification.

2.2.1 By-product from sugar production

Several products are produced from crushing sugarcane at the sugar factory. These primarily include bagasse, molasses, filter cake, and trash. The yield of these residues is shown in Table 2.2.

Table 2.2 Sugarcane residues yield per t of raw sugar produced

Sugarcane residue	Yield per t of raw sugar produced
Trash remaining in field (50% moisture), t	1.85
Trash at the clean center (50% moisture), t	0.57
Bagasse (50% moisture), t	2.57
Molasses, t	0.40
Filter cake, t	0.30
Residual water, m^3	5.00

Source: Alonso et al. (2007)

(1) Bagasse

Bagasse is the fibrous portion of sugarcane that remains after the juice has been removed. It has several applications as follows:

- Burning bagasse to produce steam generating power for sugar factory
- Bagasse is used for paper making

- Bagasse is also used as an animal feed

Further chemical treatment of bagasse can be used to produce other by-products. These include production of various fermented and chemical derivatives of cellulose, and fermentation of bagasse to produce fuel ethanol (Allen et al., 1997).

(2) Molasses

Molasses is the thick syrup residue left over after the sucrose has been removed from the clarified sugar juice (syrup). The final molasses is used as a stock feed supplement, and a fertilizer for sugarcane field (Office of the Gene Technology Regulator, 2004). Molasses can be used for ethanol production.

(3) Filter cake

Filter cake is the solid residue from sugarcane juice filtration. It can be used as fertilizer for sugarcane field.

(4) Trash

Trash refers to the sugarcane plant material left over after harvesting. It is generally retained in the sugarcane field as mulch. As well, sugarcane trash and bagasse can provide a significant amount of biomass for electricity generation. By burning sugarcane trash and bagasse in boiler, the steam is obtained to drive turbine and process of sugar juice as well as generating electricity.

2.2.2 Renewable energy production

Ethanol produced from sugarcane juice and molasses (Table 2.3) can be used as fuel for vehicle and machinery. This ethanol can be mixed with gasoline to make a gasohol (a blend of gasoline and alcohol). This is one alternative way for Thailand to lessen dependence on oil import. This would alleviate the country's trade deficit and it would affect the Thai economic as a whole.

Table 2.3 Amount of production and residues of milled sugarcane per 100 t basis

Sugarcane product and residues	Potential availability as per 100 t each of milled sugarcane
Raw sugar, t	10.6-12.0
Bagasse (50% moisture), t	25.7-28.0
Trash (50% moisture), t	24.2-25.0
Ethanol from sugarcane juice, hL	70-75
Ethanol from molasses, hL	10
Biogas from filter cake, N m^3	78
Biogas from residues of alcohol production, N m^3	1486

Source: Alonso et al. (2007)

In Thailand, ethanol production from sugarcane is in line with the Thai government's policy about promotion of gasohol consumption, which aims to increase domestic consumption of ethanol around 1 million liters per day by 2006, and around 3 million liters per day by 2011 (Cane and Sugar Industry Policy Bureau, 2006).

Until 2007, seven ethanol production plants have already been in Thailand in operation with the total production capacity of 955,000 liters per day. This supply has exceeded the demand for domestic consumption, because during the last quarter of 2006 to the first quarter of 2007 the domestic consumption of gasohol was around

3.3-3.5 million liters per day, which required the amount of ethanol around 0.33-0.35 million liters per day for blending. Thus, the Thai government has undertaken various promotions to enhance the gasohol consumption. It is necessary for the Thai government to make consumers' confidence in the use of gasohol, in order to boost the demand on ethanol to meet the target. In July 2007, the domestic consumption of gasohol has increased to 4.6 million liters per day. This means, daily amount of 0.46 million liters of ethanol was consumed (Office of the Cane and Sugar Board, 2007). It could be noted that, the Thailand's ethanol production in 2007 still exceeds the demand for domestic consumption. In this regard, ethanol producers are now requesting the government to set a clear mandate on domestic consumption of gasohol, and to allow the export of the oversupply ethanol.

2.3 Situation of Thai sugar industry and outlook

The main determinant of growth in Thai's sugar output and export is likely to be the Thai's government policies affecting price of sugarcane, sugarcane's production cost, as well as use of ethanol. These policies may be affected by trends in international prices of sugar and crude oil.

With high variability in the international sugar price, sugar industries in Brazil, Australia, Thailand, and South Africa have been exploring co-generation of other products from sugarcane. These include ethanol, electricity, animal feed and fiber boards (Higgins et al., 2007). The petroleum crisis causing high price of petroleum has made ethanol a more attractive alternative. Ethanol requirements are expected to increase in the near future as international petroleum prices increase. Accordingly, the future volume of sugar in the world sugar market depends heavily on the balance between sugar and ethanol production. The ethanol industry could slow down increasing of sugar supplied to the world sugar market. This will significantly affect on world sugar price.

2.4 Practical features of sugarcane production in Thailand

2.4.1 Contract farming in the Thai sugarcane production

Most of sugar factories in Thailand have their own lands to produce sugarcane because they want to make sure that their factories will have enough sugarcane that they need. Alternatively, they also collect certain amounts of sugarcane from sugarcane farmers for their factories via middleman. In this regard, sugar factory will provide fertilizer, pesticide, and money for farmers through the middleman. Also, middleman will mange land preparation, labors for planning and harvesting, and trucks for transporting sugarcane to the factory. A loose agreement on the amount of sugarcane to be delivered is usually done between sugar factory and middleman (Naritoom, 2000). These could be stated that contract farming is important for Thailand's sugarcane production. The contract farming gives high potential to sugarcane farmers because they can get more supports (material, technology, and technical assistance) from government agencies. As well, sugarcane farmers feel more secure with the product price. Meanwhile, sugar factories can receive high potential via contract farming. They can collect sufficient sugarcane to serve their plants and enough production for export.

2.4.2 Practical features of the Thai sugarcane cultivation

Sugarcane is planted by placing stalks of sugarcane in open furrows. At each plant node, these stalks have buds or eyes from which new plants develop. As sugarcane plant matures throughout the growing season, the amount of sucrose in the cane increases. Most of this sucrose production occurs when the plant is fully mature and begins to ripen (Alexander, 1973).

Sugarcane is usually harvested by cutting stems close to the ground around 12-18 months after planting. It is routinely harvested before flowering as the process of flowering leads to reduction in stem's sugar content (Bull, 2000).

Sugarcane crops are generally classified based on its current year or stage of crop cycle. From the planting through the first harvest, a sugarcane crop is referred to as a planted cane crop. After the first harvest, the root system or ratoon that remains in the ground will re-sprout from each stalk. Succeeding crops are referred to as stubble crops. First stubble, for example, would refer to a sugarcane crop in its first year of stubble or re-growth after the first harvest. After each subsequent stubble within a crop cycle, sugar yield generally decreases until low enough that it is more economical to plough out and plant a new crop (Salassi et al., 2002). This means, although several stubble crops are possible, damage from harvesting and weed control operations as well as the impact of pests and diseases eventually lead to declining yield. Thus, a maximum of four stubble crops are typically grown before plough out the crop and replanting (Bull, 2000).

At the grower level, profitability is sensitive to the number of stubbles before ploughing out. With an increased sugar price, it is more economical to plough out after a smaller number of stubbles, since planting costs have a less significant influence on profitability. When ploughing out after a smaller number of stubbles due to a higher sugar price, the profitability increase is accelerated (Higgins et al., 2003).

In Thailand, a maximum of two or three stubble crops before plough out and replanting are generally found. Several Thai's sugarcane breeders have being developed new sugarcane varieties which give more productive yield per unit area as well as sugar content in stalks, because an increase in sugar yield and CCS (Commercial Cane Sugar, the percentage of extractable sugar from cane using commercial standard practices) will result in profitability to both sugarcane farmer and sugar factory. So far, there are many Thai sugarcane varieties which suitable for cultivation in central, eastern, northern, and northeastern of the country; such as Chainat-1, Uthong-1, Uthong-2, Uthong-3, Uthong-4, K84-200, K88-92, K90-77, KU-50, and so on.

2.5 Type of sugarcane harvesting in Thailand

The sugarcanes are harvested annually, using either hand cutting or mechanical harvesting. When cutting by hand, a machete type of knife is used. It has been used for cutting and harvesting a standing crop since the beginning of agriculture (Persson, 1987). Traditional harvesting involves leaf burning prior to harvest in order to facilitate the hand-cutting of sugarcane. In the 1950s, sugarcane producer in Australia began experimenting with combine sugarcane harvester (Churchward and Belcher, 1972; cited by Salassi et al. (2002)). The original mechanical harvesters were designed to cut burned sugarcane, as were the whole-stalk harvester. In the 1970s, considerable attention in Australia was being focused on developing a combine harvester which would harvest green sugarcane (Churchward and Poulsen, 1988; cited by Salassi et al. (2002)), because pre-harvest burning leaf results in a significant emission of greenhouse gases. Now mechanical sugarcane harvesting does not involve leaf burning. Sugarcane leaves are currently concerned as a considerable biomass, which are mulched on the soil surface, allowing a possible increase in soil organic carbon (Razafimbelo et al., 2006), promoting moisture conservation, weed control, and cost savings in cultivation. The main disadvantage of green harvesting is potential to deliver more extraneous plant material to sugar factory, thereby reducing sugar recovery.

In Thailand, there are two common types of sugarcane harvesting system currently being used: (1) Manual harvesting and (2) Mechanical harvesting.

Traditional manual harvesting is whole-stalk cutting. Prior to the harvesting operation, burning sugarcane to remove leaves and other extraneous matter is still predominant. Since burnt sugarcane can be more easily cut by workers, it is easier to find workers to cut burnt fields. The capacity of manual harvesting depends on field condition before the operation such as burned or unburned, and the percent of lodging cane. For the manual harvesting system, a grab loader is widespread used to load the harvested sugarcane stalks into trucks or wagons pulled by tractors (Figure 2.1).

Mechanical harvester can be divided into 2 types: whole-stalk harvester and chopper harvester. The chopper type mechanical harvester is more widespread in Thailand, because the whole-stalk harvester has to work with a loader. With mechanical whole-stalk harvesting, stalks of harvested sugarcane would be piled into rows after harvest and then loaded by using a grab loader. Meanwhile, the chopper cuts one row of cane per swath at a rate of about 45 t per hour. Sugarcane stalks are cut into 12–14 inch billets and loaded into truck by using a loading elevator, mounted on the chopper. An extraction fan system on the chopper strips and removes leaf and other extraneous matter from the sugarcane prior to loading into trucks. When sufficient numbers of trucks are available, the chopper can harvest the field continuously (Figure 2.2).

Figure 2.1 A grab loader

So far, mechanical harvesting has been commonly practiced in developed countries (Australia, United States, etc.) and Brazil. However, in Thailand, mechanical sugarcane harvesting stays at an initial stage on development. Although mechanical sugarcane harvester has much higher field capacity compared to traditional manual cutting practice, it necessitates more investment. The price of an imported mechanical harvester is very expensive as much as around 217,000 US$ (Salassi and Breaux, 2001). Thus, manual cutting practice is still widely employed in Thailand. However, mechanical sugarcane harvesting has attracted practical concerns in the field due to improved timeliness in order to cope with seasonal shortage of labor during the harvesting season. People believe that such a mechanical power is able to reduce harvesting and handling costs caused by a large group of immigrant labor and their accommodation expenditure.

Figure 2.2 The chopper-type mechanical sugarcane harvester

2.6 General aspect of sugarcane transportation in Thailand

In Thailand, the cost of sugarcane transportation occupies a large portion of the total sugarcane production cost. Thai sugarcane farmers have to bear the cost for delivering their harvests from their farms to sugar factory by themselves. The harvested sugarcanes are transported to the sugar factory by a truck system. Six-wheeled and ten-wheeled trucks that have legal loading capacity of 10 t and 21 t are usually used. However, trucks tend to be overloaded to keep down the transportation cost and to maintain the quality of fresh harvested sugarcanes. In general, trucks owners operate this process as middleman. The transportation cost will vary depending on fluctuation of fuel price. It was usually found that in the middle of harvesting season, sugarcane supply is peak and higher than milling capacity of sugar factory, then hundreds of trucks have to wait long hours in front of sugar factory (Takigawa et al., 2005).

2.7 Literature review of supply chain research in sugar industry

Increased international competitiveness and lower commodity prices in recent decades (Boehlje, 1999) have led to agricultural industries exploring value chain opportunities to increase profitability and sustainability. Sugar industries around the world are no exception. In addition, sugar production (per unit area) has remained constant or declined over the past three to five decades in many countries (Meyer and Van Antwerpen, 2001; Garside el al., 2001; cited by Higgins (2007)). These pressures have led to an increased focus on supply chain solutions to increase profitability.

A literature review of supply chain research in sugar industry conducted to date highlighting the opportunities and benefits is provided in following subsections.

2.7.1 Sugarcane simulation models

In many countries, quantity and quality of sugarcane are used as determining factor for pricing the products. Payment to sugarcane farmers is based on weight and sucrose content in stalks. Therefore, utilization of sugarcane simulation models for farm management or harvesting operation requires incorporating the simulation of stalk weight and sucrose level in stalk. The model must be capable of simulating cane yield response to flexible planting and harvesting date.

There are three main sugarcane simulation models currently in use throughout the world, excluding the more numerous regression-type models utilized in site-specific studies. The models are an Australian model APSIM-Sugarcane (Keating et al., 1999), a South African model CANEGRO (Imman-Bamber, 1995), and another Australian model QCANE (Liu and Kingston, 1995). The former two models have similar origins and some have precursor older models that are still in use. For example, AUSCANE is a precursor to APSIM-Sugarcane. Now CANEGRO exists in two variations: (1) SASEX as a research tool for interactive multi-year simulations (2) DSSAT that has been coupled to soil-and-plant nitrogen model from the CERES-Maize model.

AUSCANE and APSIM-Sugarcane have been developed using the radiation use efficiency (RUE), while others simulate the components of photosynthesis and respiration. QCANE simulates growth and sugar accumulation in daily steps and differs from other sugarcane models in its comprehensive treatment of the physiological processes. QCANE integrates the process of canopy development, photosynthesis and the partitioning of carbohydrates to plant organs for growth, respiration, and sugar accumulation (Liu and Bull, 2001). McWilliam et al. (1990) reported that the RUE-type sugarcane model was weak in biological component involved in the simulation of biomass and sucrose accumulation.

All the models did have one common objective to simulate sucrose yield. They have performed reasonably well, but the prediction of sucrose yields were not the same. O'Leary (2000) examined the three models (APSIM-Sugarcane model, CANEGRO, and QCANE) and reported that mean errors of prediction (root mean square of residuals) for sucrose yield for APSIM-Sugarcane model were 4.12 Mg/ha, for CANEGRO 6.07 Mg/ha and for QCANE 2.51 Mg/ha. More amendments to sucrose partitioning under water and nitrogen-stressed conditions are needed.

Otherwise, Timm et al. (2003) used a first order state-space model to improve understanding on the relationships among sugarcane yield parameter, such as the number of canes per meter of row, and physical-chemical soil properties such as available phosphorus, calcium, and magnesium, clay content and aggregate stability. This study aimed to search for an optimal management of soil resources and crop yield for sugarcane production in Brazil. Results show that all of the used state-space equations described the spatial distribution of number of canes better than the equivalent multiple regression equations.

2.7.2 Simulation in sugarcane harvesting and transportation

Sugarcane must be harvested within certain periods of crop maturity and, once harvested, the sugarcane should be milled within 24 h to preserve weight, sugar content, and juice quality. These make sugarcane harvesting and transportation system complex, as well as, the system includes daily planning of areas to harvest, and allocating labors and machineries for harvesting, loading, and delivering the sugarcane from the plantation to the sugar factory.

Whitney and Cochran (1976) developed models for sugarcane harvesting and transportation system. They used queuing theory to predict delivery rates of the harvests. Their models are for a transport system of tractors and wagons and one continuous road between the farm and the sugar factory. Loading times were assumed as an exponential distribution, and arrival times at the farms were Poisson distributed. Outputs of their models were nomographs that can be used to predict the rate at which sugarcane can be delivered from the plantation.

A computer simulation model for mechanical harvesting and transporting of sugarcane for a system of single harvester and multiples trucks, in the Mae Klong river basin of Thailand, has been developed by Singh and Abeygoonawardana (1982). The model was based on characteristics of sugarcane fields, a time utilization study of harvesters and a performance evaluation of the trucks used for transport and the cost component of the operations obtained either from the farmers or from the Massey Ferguson agents in Thailand. The simulation model indicated that at least four transport trucks are required for economic operation, but increasing the number of trucks to more than ten would be uneconomical for a field to mill distance of less than 45 km.

A PC-based decision support system (DSS) was developed by Singh and Pathak (1994), in order to assist in decision making in management of the chopper-type mechanical sugarcane harvesting system in Thailand. The DSS could calculate the harvesting costs for a given set of conditions. This DSS provided a useful means for making optimum decisions for economic use of the chopper and its management.

Salassi and Champagne (1998) developed a spreadsheet-based model to estimate equipment requirements and costs associated with the mechanical harvesting and hauling of sugarcane. The model was capable of estimating equipment requirements and costs for whole-stalk sugarcane harvester as well as for chopper-type harvester. Costs of hauling harvested sugarcane to sugar factory were estimated for both direct hauling systems (tractor and wagons) and transfer hauling systems (trucks and trailers).

Reduction in time utilized between harvesting and milling is important due to deterioration in cane quality after harvesting. Semenzato (1995) developed a simulation algorithm for scheduling the operations and planning the resources, in such a way that the lapse of time between end of burning and processing is minimized. This algorithm can be used as a basis for a decision support system. Hansen et al. (1998; cited by Higgins (2007)) emphasized their simulation method achieving up to a 40% reduction in duration between harvesting and processing in a South African case study, by coordinating harvest and delivery activities with total cane delivered to sugar factory.

Arjona et al. (2001) developed a discrete event simulation model of the harvesting and transportation system of a sugarcane plantation in Mexico that covers all processes from the burning of the cane to its unloading at the processing line. Components of an activity model are entities, waiting lines, activities and entity flows. The model was developed to solve a problem with the amortization of machinery used in the plantation. The solutions showed that machinery is underutilized and found possible solution to the problem. The resolutions involve increasing the efficiency of machinery use, thereby allowing a reduction in the number of machinery without increasing sugarcane processing times.

2.7.3 Optimization in sugarcane harvesting and transportation system

The sugarcane harvesting and transportation system has varying scales of decision making between farm and factory levels. This system needs not only advanced machines and agricultural techniques, but also the cooperation of all tasks in harvesting system. The delay of any tasks could affect the working efficiency of whole system. Thus, there were some researches applied mathematical optimization techniques, such as linear programming or integer programming, to determine the best possible decisions on when to harvest given the yield and quality attributes of each fields, as well as restrictions associated with transport and milling capacity.

An application of an optimization model with the objectives of maximizing sugar yield and net revenue in relation to harvesting date and crop age was presented by Higgins et al. (1998). Their results showed that an application of the model to maximize sugar yield showed a 4% increase in sugar yield compared to current practice, but a 23% decrease in net revenue due to a shorter crop cycle with less ratoons before replanting. Optimizing with respect to net revenue, gave a 3% gain in sugar yield with an 8% gain in net revenue. These could be concluded that there is scope for optimizing harvest date to improve profitability.

Salassi et al. (2002) developed crop yield models and a mixed integer mathematical programming model to evaluate the impact of alternative sugarcane yield and quality scenarios on the optimal harvest system selection. Their estimated models were used to predict stalk weight and sugar content per stalk at various points in time throughout the harvest season. Results indicated that predicted values of stalk weight increase 10-20%, while sugar content per stalk increases by more than 50%, throughout the harvest season. Predicted sugarcane crop yield values were incorporated into a mixed integer mathematical programming model which maximized whole farm net returns. The model incorporated pre-harvest and harvest field operations, and selected equipment complement necessary to perform these operations. Results from the mixed integer harvest system selection model verified that the optimal selection of a sugarcane harvesting system is dependent on yield of specific variety, field recovery of the harvesting system, and the impact of leaf trash and other extraneous plant material on the recovery sucrose from the cane stalks. The results indicated that the chopper-type mechanical harvesting system was found to generate higher net returns than the whole-stalk harvesting system. Although the sucrose recovery was lower for the chopper, the ability to recovery and delivering more metric t per hectare resulted in greater net returns.

Higgins et al. (2004) developed a framework for integrating a complex harvesting and transportation system for sugar production by applying techniques in operation research, financial modeling, and simulation. A modeling framework was developed in order to improve existing inefficiencies resulted from excessive number of mechanical harvesters owned by harvester contractors and sugarcane farmers, and the fact that most harvesters operate too short time a day. Through reducing the number of harvesters in their study sites (Plane Creek and Mourilyan in North East

Queensland, Australia), and implementing best practice principles for harvesting, potential gains in profitability of up to 1 million AU$ per annum was shown.

Several advocated a comprehensive systems approach for using seasonal climate forecast system (such as daily rainfall, temperature radiation, wind and humidity) to improve risk management and decision making capability across all sugar industry sectors. Everingham et al. (2002) pointed out that there are the need for climate forecast systems to target the varying needs of sugar industries, and the need to consider the whole industry value chain. Astika et al. (1999) developed an algorithm to schedule sugarcane harvesting system based on short range weather variation. Genetic algorithms were utilized for optimization in order to determine daily amount of harvested canes, to decide fields to be harvested and allocation of harvesters.

So far, there has been an increase in the adoption of improved logistics of the sugar industry. However, model developed in one country are not always applicable to others due to differences in business structure between farming and processing, the level of mechanization in harvesting, and the infrastructure of transport system.

Chapter 3

Mechanization for the improvement of the sugarcane harvesting and transportation systems in Thailand

3.1 Introduction

Sugarcane is a crucial economic crop of Thailand. It is a perennial crop grown mainly as a source of sugar. The procedure for processing sugar involves harvesting the sugarcane stalks, then shredding them and extracting the sugarcane juice. Raw sugar is produced from the juice and is later refined into white sugar. Thailand produces sugar as an export commodity, the income from which is a source of foreign currency for Thailand and has supported its industrial development. Thailand is the second largest sugar exporter in the world. In 2004, the total export of white and raw sugar was 4.55 million t, and the total value of exported sugar was 844.48 million US$, or 32.09 billion baht (1US$ equals to 38 baht).

It should be noted that the cost of sugarcane harvesting and transportation constitutes a large portion of Thai sugarcane's total production cost, with the average cost of sugarcane harvesting in Thailand accounting for 66% of the total labor cost, or equivalent to 35% of the total cost. The average cost for sugarcane transportation was 2.79 US$/t, or 106 baht/t in 2003 (Office of Agricultural Economics, 2003). Nearly half of the total cost is devoted to harvesting and transportation. Ultimately, both harvesting and transportation costs are determinant factors of sugar's domestic consumer price and international export value.

The high cost of sugarcane harvesting and transportation is one of the reasons for the reduction in the total amount of Thailand's sugarcane cultivation. Farmers who have small fields and/or whose fields are located far from a sugar factory tend to abandon sugarcane cultivation. Such farmers have changed their cultivation into other crops that have lower production costs, such as cassava.

The Thai government has made an attempt to reduce this high cost of sugarcane harvesting and transportation. For this purpose, the Office of Agricultural Economics (OAE) established a loading station in Khon Kaen province to facilitate the supply of sugarcane to the sugar factory for all sugarcane farmers, particularly farmers with small acreages. Because most sugarcane farmers do not possess a truck and normally have only a small vehicle, it is difficult for them to transport their products from their farms to the sugar factory by using their own vehicles, instead having to rent a truck and pay the hiring cost for cutting, loading, and transporting. In the operation of the loading station, sugarcane farmers are required to transport their products from their fields to the station by themselves. Since the loading station is located in the neighborhood of sugarcane fields, sugarcane farmers with small acreages could transport their products from their farms to the loading station by using their own vehicles instead of hiring a truck, thus reducing transportation costs. The sugar factory collects the sugarcane from the loading station and transports it to the processing plant, this process being managed and operated by the sugar factory. The sugarcane farmers have to pay the standard cost of 2.24 US$ (or 85 baht) per t for the transport of their products from the station to the sugar factory. Supplying sugarcane to the sugar factory via the loading station could reduce the harvesting and transportation costs of sugarcane farmers by around 20% when compared with the traditional system in which the costs include direct delivery from the field to the sugar factory (Paitoon et al., 2001). However, investment in the loading station to cover all regions in the country is expensive, the initial investment in one loading station being approximately 289,474 US$, or 11 million baht. Thus we see that the problem of the decrease in sugarcane cultivation cannot be solved through the use of loading stations alone. The decline in the amount of sugarcane cultivation persists, and has resulted in a reduction of sugarcane volume; approximately 16,668,269 t were reduced in 2005, while approximately 1,126,370 t were reduced in 2006 (Office of the Cane and Sugar Board, 2006).

Improper harvesting and/or delay in transportation will result in the crop's deterioration. When harvested sugarcane has to be left in the field due to a lack of transportation vehicles, the sugarcane's quality deteriorates significantly, resulting in a decrease in the sugarcane farmer's income. Deterioration caused by sugarcane being left in the field also leads to a reduction in the amount of sugar produced, thus reducing the income of the sugar factory. This shows that harvesting and transportation efficiency directly influences the income of sugarcane farmers and the owners of sugar factories.

To determine the shortcomings in the harvesting and transportation processes, a field survey by means of interviews were conducted from March to December 2005 in northeastern Thailand. Various data including field size, distance to a sugar factory, and geographical location of sugarcane plots were directly measured and collected. The time studies on harvesting and transportation operations were also carried out in December 2005. Simulation analyses using a simple sugarcane harvesting and transportation were performed in order to examine how the proper use of chopper-type mechanical sugarcane harvesters could improve the efficiency of the harvesting and transportation system.

3.2 Study site and methodology

3.2.1 Study site

The survey was conducted in Udon Thani province in northeastern Thailand. The topography in this region can be characterized by hilly land with steep slopes. Annual precipitation amounts about 1200 mm and hence it enables to provide sufficient water rain-fed farming. The temperature ranges from 20 to 38 degrees Celsius year around. The major crops cultivated on gently sloping fields are sugarcane and cassava, whereas farmers have grown rice for private use in lower areas.

Due to the abundance of sugarcane cultivation in this area, there are 15 sugar factories in the nine provinces of the northeast region, and 3 sugar factories in Udon Thani province. In the crop-year 2005-2006, 3.20 million t of sugarcane were processed in the 3 factories, representing 21 percent of the northeast region’s total production (Office of the Cane and Sugar Board, 2006).

The study site is located within 102°50’36.0’’E-102°56’4.2’’E and 16°59’57.6’’N-17°5’24.5’’N, which corresponds to an area of 10 km by 10 km (Figure 3.1).

3.2.2 Survey methods

General data regarding sugarcane production in Thailand were collected from the Office of Agricultural Economics (OAE) under the Ministry of Agriculture and Co-operatives, and the Office of the Cane and Sugar Board (OCSB) under the Ministry of Industry. The data are useful for examining the general tendencies concerning the amount of annual sugarcane harvested, the amount of sugar produced, and production costs as mentioned in the previous section. However, the shortcomings in the local sugarcane supply process cannot be clarified based directly on this information.

The first interview from sugarcane specialists and farmers was performed in March 2005; along with the survey, the fields were examined after the harvesting season.

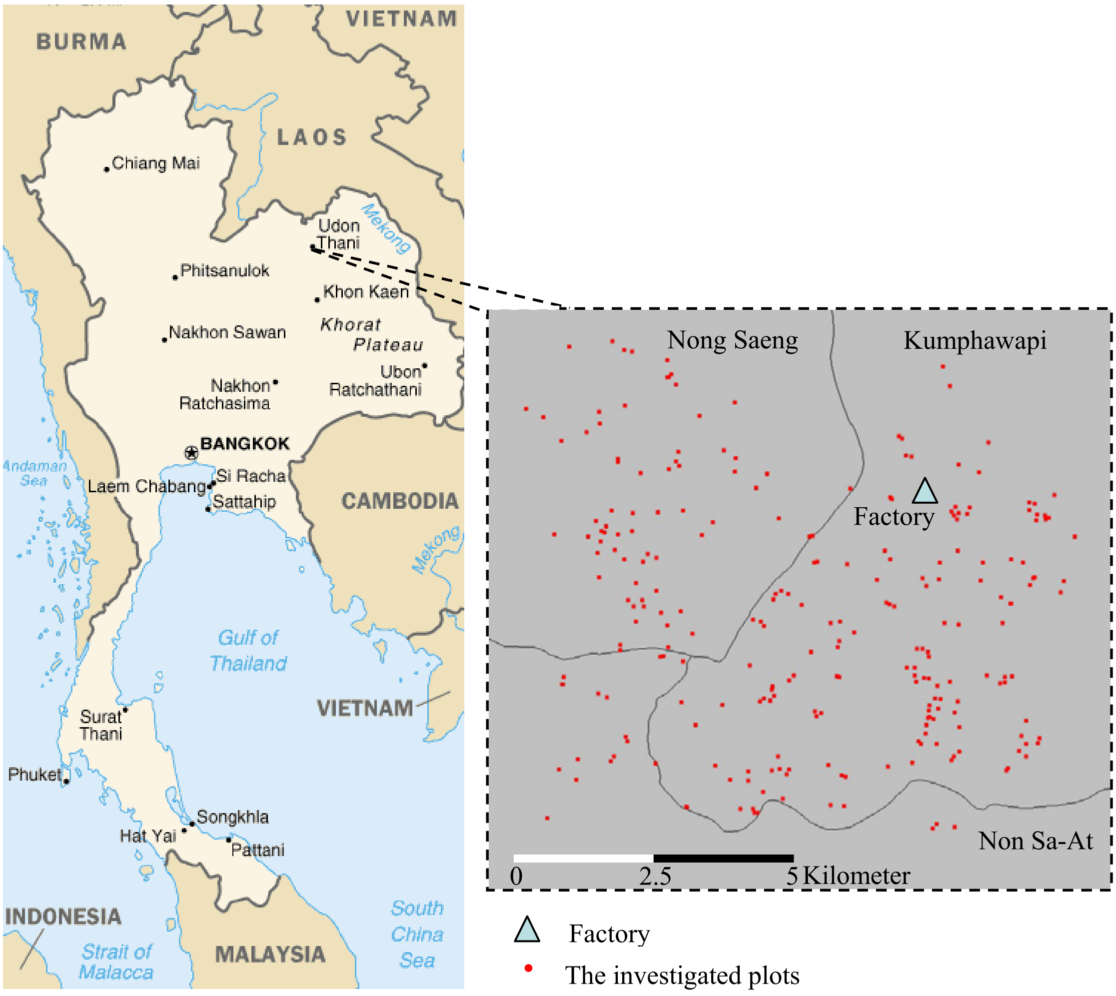


Figure 3.1 Location of study area

In July 2005, sugarcane farmers and workers were interviewed. Interview items included the farmer's personal history, crop type, sugarcane variety, acreage under cultivation, history of cropping patterns, agricultural machinery owned, and operating cost and hours of farming operations. Additional information regarding the sugarcane plot was collected via questionnaire. The items used in the interview section of the survey are listed in Table 3.1.

Table 3.1 Detail of questionnaire

Item asked the farmers	Data of each plot to be investigated
Farmer's name	Plot size
Farmer's address	Variety name
Number of sugarcane plots	Crop type
Type of water source	Planting date
Fertilization	Plot's address
	Distance to a sugar factory
	Geographic information covering latitude, longitude, and altitude

The field investigation was performed from August through December 2005. Two topographic map sheets on a 1:50,000 scale published by the Royal Thai Survey Department (Sheet numbers: 5542I and 5543II) and twelve aerial photos on a 1:25,000 scale were used to locate fields in the surveyed region. Since the characteristics of the field and the distance of the field from the factory affect the costs of harvesting and transportation, a GPS receiver and laser distance meters were utilized to further determine the fields' locations and to measure the plots' dimensions.

We conducted our field investigation in collaboration with the staff of the K sugar factory, one of the factories located in the study site. The daily milling capacity of the K sugar factory that had been registered with the OCSB was around 10,211 t of sugarcane (Office of the Cane and Sugar Board, 2006).

In December 2005, time studies regarding the harvesting and transportation operations were also carried out. The cutting speed of the chopper and the time required for mechanical harvesting operations (consisting of the turn around time of the chopper and truck at the head land and time for truck changing), as well as the time required for the truck's trip to the factory and time spent at the factory were measured.

The total number of farmers who responded to the questionnaire was 117. All of them usually supplied sugarcane to the K sugar factory. The dimensions of 248 sugarcane plots were measured. The total area of these fields was 617.76 ha or 3,861 rai (rai is an area unit of Thai, and 1 rai equals 0.16 ha or 1,600 m^2).

3.3 Results of interview and field investigation

3.3.1 Present state of sugarcane harvesting and transportation in Thailand

This section discusses the present state of sugarcane harvesting and transportation based on the results of the field investigation which was conducted in the sub-district (Tambol in Thai) of 3 districts (Amphoe in Thai): Kumphawapi, Nong Saeng, and Non Sa-At. Since the surveyed areas were located near the sugarcane processing plant, sugarcane was site's the main product. The study measured the distance of the road connecting the investigated field and the K sugar factory. The investigated sugarcane fields were distributed in a range of 0.1 to 22 km from a sugar factory.

(1) Cultivation data

Five varieties of sugarcane were cultivated in this region. Cultivation acreage and each crop variety are shown in Table 3.2. K88-92, a main sugarcane variety of northeastern Thailand, had the largest cultivation acreage, occupying 67% of the total surveyed area. This variety was found in every village surveyed.

The area of newly planted sugarcane occupied 62% of the total sugarcane production area in the site. Meanwhile, the percentages of the areas cultivating first stubble, second stubble, and third stubble were 33%, 4%, and 1%, respectively.

(2) Supply of sugarcane

Table 3.3 shows the amount of sugarcane unloaded daily at the K sugar factory. This table shows the four types of truck operating within the area. The average loading capacity of small 6-wheeled trucks (110 hp or 82 in kW) was 10 t, while average loading capacity of larger 6-wheeled trucks (135 hp or 101 in kW) was 15 t. These two types of 6-wheeled trucks usually transport whole stalk sugarcane. Meanwhile, the average loading capacity of 10-wheeled trucks was 24 and 15 t when delivering whole stalk sugarcane and chopped sugarcane, respectively. In the case of a 10-wheeled truck with a trailer, the average loading capacity was 42 and 28 t when delivering whole stalks and chopped sugarcane, respectively. Approximately 60% of the sugarcane processed daily at the K sugar factory was transported by 10-wheeled trucks.

Table 3.2 Cultivation acreage of sugarcane in study site

Crop type	Type of data	Sugarcane variety					Total
		Ehiew	85-2-072	K88-92	Uthong	Uthong 5	
New planting	Sum of field size (ha)	1.60 (10)[†]	7.68 (48)	243.92 (1,524.5)	110.32 (689.5)	21.28 (133)	384.80 (2,405)
	Number of plot	1	3	113	55	4	176
First stubble	Sum of field size (ha)	1.28 (8)		142.24 (889)	59.84 (374)	1.6 (10)	204.96 (1281)
	Number of plot	1		35	27	1	64
Second stubble	Sum of field size (ha)			24.48 (153)			24.48 (153)
	Number of plot			7			7
Third stubble	Sum of field size (ha)			3.52 (22)			3.52 (22)
	Number of plot			1			1
	Total sum of field size (ha)	2.88 (18)	7.68 (48)	414.16 (2,588.5)	170.16 (1,063.5)	22.88 (143)	617.76 (3,861)
	Total number of plot	2	3	156	82	5	248

[†] Figures given in parentheses are the sum of field size in area unit of Thai (rai).

Table 3.3 Daily amount of unloaded sugarcane at the K sugar factory classified by truck type

Type of truck	Type of harvesting method	Number of unloading, times		Daily amount of sugarcane, t	
		Green	Burned	Green	Burned
Small 6-wheeled truck (110 HP)	Manual	28	20	287.28	208.24
10-wheeled truck	Manual	117	166	2,849.76	3,873.70
10-wheeled truck with trailer	Manual	36	50	1,506.93	2,104.40
10-wheeled truck	Mechanical	87	1	1,333.79	4.26
Big 6-wheeled truck (135 HP)	Manual	14	7	206.67	96.21
	Total	282	244	6,184.43	6,286.81

Manual harvesting is still the primary harvesting mode in Thailand, and is also predominant in the present study site. Field survey results showed that approximately 89% of the sugarcane processed daily at the K sugar factory was manually harvested, while the remaining 11% was mechanically harvested.

Since burnt sugarcane can be more easily cut by workers, it is easier to find workers to cut burnt fields; 53% of the total harvested sugarcane of Thailand was burned in 2005 (Office of the Cane and Sugar Board, 2006). The same tendency was found in the study area; the percentage of harvested sugarcane burned prior to manual cutting was approximately 50% as shown in Table 3.3.

The K sugar factory processes both whole stalks and chopped sugarcane and has 10 unloading lines. There is one priority line specially provided for trucks unloading chopped sugarcane. In this unloading line, the waiting time was shorter than those in other lines. Since unloading chopped sugarcane can be finished relatively quickly, those trucks carrying chopped sugarcane can more quickly return to the fields to be reloaded. Trucks operating in conjunction with a chopper received the highest unloading priority in order to reduce the chopper's pause time. This indicates that the sugar factory seeks to support mechanical harvesting.

(3) Mechanization of harvesting and transportation

When the mechanization levels of the farmers were compared, large-scale farmers were found to possess mechanical harvesters, four-wheeled tractors, trucks, and other machinery (Figure 3.2(a)), while the small-scale farmer's owned a relatively minimal number of machinery.

(a) Yard of a large-scale farmer

(b) A chopper harvester operates with a truck

Figure 3.2 Mechanization status in the study site

Though few data exist regarding the number of harvesting machines operating in Thailand, we found that in our survey area, 6 mechanical sugarcane harvesters, the chopper type, were working, and that they were owned by 3 large-scale sugarcane farmers. The chopper-type mechanical sugarcane harvester usually operates in concert with trucks. Sugarcane stalks are cut into 12-14-inch billets and loaded, by using a loading elevator mounted on the chopper, into a truck that keeps its orientation parallel with the chopper (Figure 3.2(b)). When sufficient numbers of trucks are available, the chopper can harvest the field continuously. Our survey found that there were 38 units of 10-wheeled trucks, and 8 units of 10-wheeled truck paired with trailers, which were owned by the 3 large-scale sugarcane farmers.

Approximately 97% of the farmers in the study site do not own harvesting machines, with most not having adequate numbers of manual workers and trucks. Thus, they usually outsource the harvesting and transportation processes by hiring middlemen who provide labor and machinery. Two of three large-scale sugarcane farmers would work as middleman when they had finished harvesting their own fields. The field survey found that it was difficult for farmers to find cutting workers, particularly for green sugarcane harvesting, while it is not difficult to hire mechanical sugarcane harvesters and trucks from middlemen. The hiring of mechanized resources for the harvesting and transportation processes is becoming a common practice.

The data regarding workers actually engaged in harvesting showed that the hiring cost of mechanical harvesting was less than that of manual harvesting. The data obtained from the sugarcane workers showed that the cost of manual harvesting and loading burned sugarcane was around 148 US$/ha, or 900 baht/rai, while in the case of green sugarcane, the hire cost was around 197 US$/ha, or 1,200 baht/rai.

Meanwhile, the hiring cost of mechanical harvesting was about 140 US$/ha, or 850 baht/rai for both burned and green sugarcane.

In addition, the survey revealed the sugarcane harvesting field capacity of the study area. The results confirmed that when using a mechanical harvester, harvesting can be completed within a much shorter time than would be required by manual harvesting. An average field capacity for mechanical harvesting was 45 t per hour. Meanwhile, the manual harvesting, cutting the sugarcane at the bottom of stalks and removing some of the tops, carried out by one cutting worker was 1 t and 2.5 t per day in an unburned field and a burned field, respectively. In the case that only the bottoms of the stalks are cut, the cutting rate performed by one worker was 5 t per day.

3.3.2 Local constraints of mechanical harvesting in Thailand

A cost comparison clearly indicates that mechanical harvesting is likely to be a key in reducing sugarcane production costs, since the survey discovered that the hiring cost of a mechanical sugarcane harvester was lower than the hiring cost involved in manual harvesting. Also, mechanical harvesting was encouraged by the sugar factory by giving priority to the line for unloading chopped sugarcane. However, local constraints such as field characteristics and transportation distance are usually considered in order to determine whether or not mechanization is worthwhile. Thus, field characteristics and the distance to the K sugar factory are discussed in the following.

All investigated fields were classified into nine datasets depending on their field size (3 levels) and their distance to the K sugar factory (3 levels). In regard to field size, since “rai” is a common Thai area unit (1 rai equals 0.16 ha) very familiar to Thai farmers and the Thai people, this unit of area was used in our field surveys in order to avoid confusion on the part of the sugarcane farmers and workers. The criteria of field size given in Table 3.4 was then classified into less than or equal 10 rai (or 1.6 ha), more than 10rai but lesser than or equal 20 rai (or 3.2 ha), and more than 20 rai.

The field investigation results showed that 46% of the investigated plots were located at distance of 5 km to 10 km from the K sugar factory. The percentage of plots located at a distance of less than 5 km from the K sugar factory was 22%, while the percentage of the investigated plots located at a distance more than 10 km from the K sugar factory was 32%. The average distance to the factory was around 10 km, with a standard deviation of around 5 km.

Table 3.4 Number of plots at various field size and distance to the K sugar factory

Field size, ha	Distance[†] to sugar factory, km			Total
	≤5	5<Distance≤10	>10	
≤ 1.6	16 (3) [††]	57 (9)	55 (10)	128 (22)
1.6<Field size≤3.2	26 (12)	32 (14)	14 (5)	72 (31)
>3.2	12 (11)	25 (23)	11 (13)	48 (47)
Total	54 (26)	114 (46)	80 (28)	248 (100)

[†] Distance to sugar factory measured in this study is distance of road connected between investigated field and the K sugar factory

[††] Figures given in parentheses are the percentage of area corresponding to accumulated plots.

In addition, the greatest percentage of field size was less than or equal to 1.6 ha (or 10 rai), comprising 128 plots or 52% of all plots in the study site (Table 3.4). The average in field size was around 2.5 ha (or 16 rai), with a standard deviation of around 2.3 ha (or 14 rai). It could be concluded that the sugarcane fields in the study site are generally small. This is an exceptional characteristic of sugarcane cultivation in Thailand when compared with other sugar exporting countries such as Brazil, South Africa, and Australia, where very large fields are cultivated. Accordingly, the difficulty involved in working and in managing the harvesting and transportation resources in many small fields might lead to Thailand's high cost of sugarcane harvesting and transportation.

However, it is possible that the use of mechanical harvesters be expanded in the study site, since the percentage of the area in which the field size is greater than 3.2 ha (or 20 rai) was 47%, while the percentage of the area in which the field size is less than 1.6 ha (or 10 rai) was around 22%, as shown in Table 3.4.

In addition, the interview data showed that the sugarcane farmers having relatively small fields usually contracted the delivery of their products to the sugar factory located near their fields. Meanwhile, the sugarcane farmers owning larger fields produce a sufficient amount of product to support delivery to more than one sugar factory. They usually deliver their products according to the contract that they sign with each sugar factory. The allocation of their products to each sugar factory depends on the support given to them by each factory.

3.3.3 Incentives for mechanical harvesting

The use of mechanical sugarcane harvesters in green sugarcane harvesting presents obvious environmental benefits. Green sugarcane harvesting will avoid air pollution, and will assist in moisture retention as well as help preserve soil fertility (Braunbeck et al., 1999). As well, green harvesting will also help to decrease the sugarcane's loss of quality because burning the sugarcane prior to its harvest, as is usually found in manual cutting, results in the loss of sucrose content (Rungrat et al., 2000). Thus, the OCSB in cooperation with sugar factories seeks to promote green harvesting in Thailand by the development of a pricing system in which a lower price is paid for the burned harvested sugarcane than for the green harvested sugarcane. Around 0.53 US$ (or 20 baht) will be deducted from each t of burned sugarcane.

In addition, the price of green harvested sugarcane in the study site will be increased 1.05 US$ (or 40 baht) per t from the basic price announced at beginning of each harvesting season. The difference in price between green and burned harvested sugarcane, around 1.58 US$ (or 60 baht) per t, is intended to stimulate the use of mechanical sugarcane harvesters in the study site. This combined with the lower hiring cost of mechanical sugarcane harvesters and the relatively higher price of green-harvested sugarcane could encourage investment in mechanical sugarcane harvesters and/or the expansion of their use.

3.3.4 Expectation of an efficient sugarcane delivery

Harvesting and transportation processes are associated with 3 groups: the sugarcane farmer, the machinery owner, and the sugar factory. Based on interviews with farmers, all the sugarcane farmers in our study site want to deliver their harvested sugarcane to a reception area at a sugar factory in a timely way. They do not want their harvested products to remain in the fields while awaiting transportation, or to be left in front of the sugar factory before unloading, because the sugarcane will be priced after it has been unloaded at the process line.

In addition, effective management planning of the many small sugarcane fields is also in the best interests of the sugar factory and the machinery owner. Based on interview data, decisions regarding regional planning are not easy for them to make alone, because they have to decide which fields are ready to harvest, how much and which mechanized resource are available, and when the operation should be completed. Thus, the sugar factory and the machinery owner need information and tools that assist in the decision-making process.

3.4 Analytical results of the simulation

3.4.1 Models simulating the mechanical sugarcane harvesting and transportation system in Thailand

To confirm the possibility of further mechanization and its effect on the profitability of sugarcane harvesting and transportation, models simulating the mechanical sugarcane harvesting and transportation system in Thailand were developed based on Singh and Abeygoonawardana (1982). For this simulation, the results obtained from our time studies and survey of trucks were used, which are listed in Table 3.5(a) and 3.5(b). The primary purpose of the simulation was to determine the most effective way to introduce mechanical sugarcane harvesters for improving the efficiency of the harvesting and transportation system.

Field characteristics such as field size, row length, amount of sugarcane, and distance to the sugar factory were used as inputs of the mechanical sugarcane harvesting and transportation simulation introduced below.

This simple simulation calculates the truck loading time, and the time necessary for the truck to arrive at the field, as explained below. Calculations concerning the deterioration time of the harvested sugarcane will be reported in a forthcoming chapter.

Table 3.5 Data used in the simulation

(a) Result of time studies in the process of harvesting and transportation

Element	Value	Unit
Average cutting speed of mechanical harvester	80	m/min
Turning time of mechanical harvester and truck at the head land	1	min
Time for truck changing	20	seconds
Driver's personal time per truck per round trip	30	min
Time spent on refueling of truck per round trip	20	min
Waiting time of truck in queue at the sugar factory	40	min
Time for reception and unloading operations at the sugar factory	20	min

(b) Surveyed data of 10-wheeled trucks

Item	Value	Unit
Loading capacity	15	Ton of sugarcane
Average traveling speed of loaded truck	65	km/h
Average traveling speed of empty truck	80	km/h
Time for sugarcane adjustment in truck	5	min

The truck loading time (TLT) is the time in minutes required to fill one truck. It can be given by

$$TLT = \left(\frac{COT}{AOS}\right)\left(\frac{FS \times 10000}{RL \times RS}\right)\left(\frac{RL}{CSP} + TTT\right) + \frac{TTC}{60}, \tag{3.1}$$

where COT is the capacity of the truck in t, RL is the row length of the field in m, RS is the row spacing of the crop which is set equal to 1.5 m, AOS is the total amount of sugarcane in the field in t, FS is the field size in ha, CSP is the average cutting speed of the chopper in m/min, TTT is the turn around time of the chopper and truck at the head land in min, and TTC is the time required for truck changing, in seconds.

Prior to transport, it was found that delays occurred when loaded sugarcane had to be adjusted in the truck. Therefore, the time for adjustment of the harvested sugarcane in the truck was also taken into consideration. The sugarcane adjustment consumed approximately 5 and 10 minutes for a 10-wheeled truck and a trailer, respectively.

A round trip time involves the travel time from the field to the factory and the return time, as well as the amount of time the truck waits in a queue at the factory, and the time for reception and unloading of sugarcane at the factory. Thus, the cumulative time for a truck to return to the field in minutes, TRTR, is given by

$$TRTR = \left(\frac{DMF}{ASF} + \frac{DMF}{ASE}\right) \times 60 + DPT + BDT + (WTM + TRO), \tag{3.2}$$

where DMF is the distance from the field to the sugar factory, km; ASF is the average speed of a loaded truck in km/h, ASE is the average speed of an empty truck in km/h, DPT is the driver's personal time per truck per round trip in min, BDT is the time spent on refueling of the truck per round trip in min, WTM is the time the truck spends waiting in a queue at a sugar factory in min, and TRO is the time for reception and unloading operations at a sugar factory in minutes. The latter term includes the waiting time required to weigh a truck loaded with delivered sugarcane, the time of the sampling test to determine the quality of the delivered sugarcane, the unloading time, and the time required to weigh an empty truck.

Based on these derived equations, further analyses were carried out in order to indicate that the field capacity of the chopper depends on the condition of the field where it is performed, and the number of trucks required for working with it. The details and results of these analyses are reported in the following sections.

3.4.2 Influence of row length on the field capacity of the chopper

In order to understand the chopper's field capacity underlying the variation in the sugarcane field's row lengths, the truck loading time, varying the values in row length from 20 m to 250 m, were calculated for given field sizes (1.6, 3.2, 4.8, 6.4 ha). The results showed that shorter truck loading times could usually be obtained when the chopper operated on fields having longer row lengths (Figure 3.3) since fields with shorter row lengths required the truck and chopper to turn more frequently at the ends of the rows.

In Figure 3.3, the results obtained from each given field sizes show the same tendencies. The truck loading time tended to decrease with the increase of row length from 20 m to 100 m. A slight decrease in the truck loading time was observed when the row length was longer than 100 m. When the chopper operated on a row length longer than 160 m, the truck loading time became lower than 30 minutes. A further increase in row length done longer than 160 m did not result in a significant reduction in truck loading time. Hence, in order to allow the effective operation of the chopper, row length should be equal to or longer than 160 m. This result was consistent with our interview results obtained from the large-scale sugarcane farmers who had much practical experience in sugarcane mechanization at the study site since 1981.

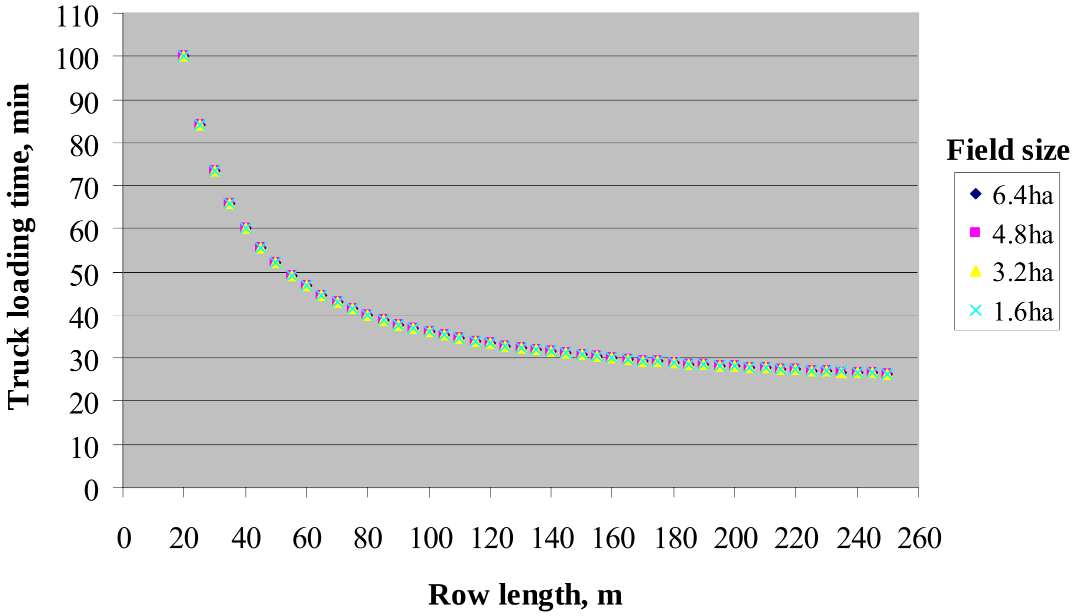


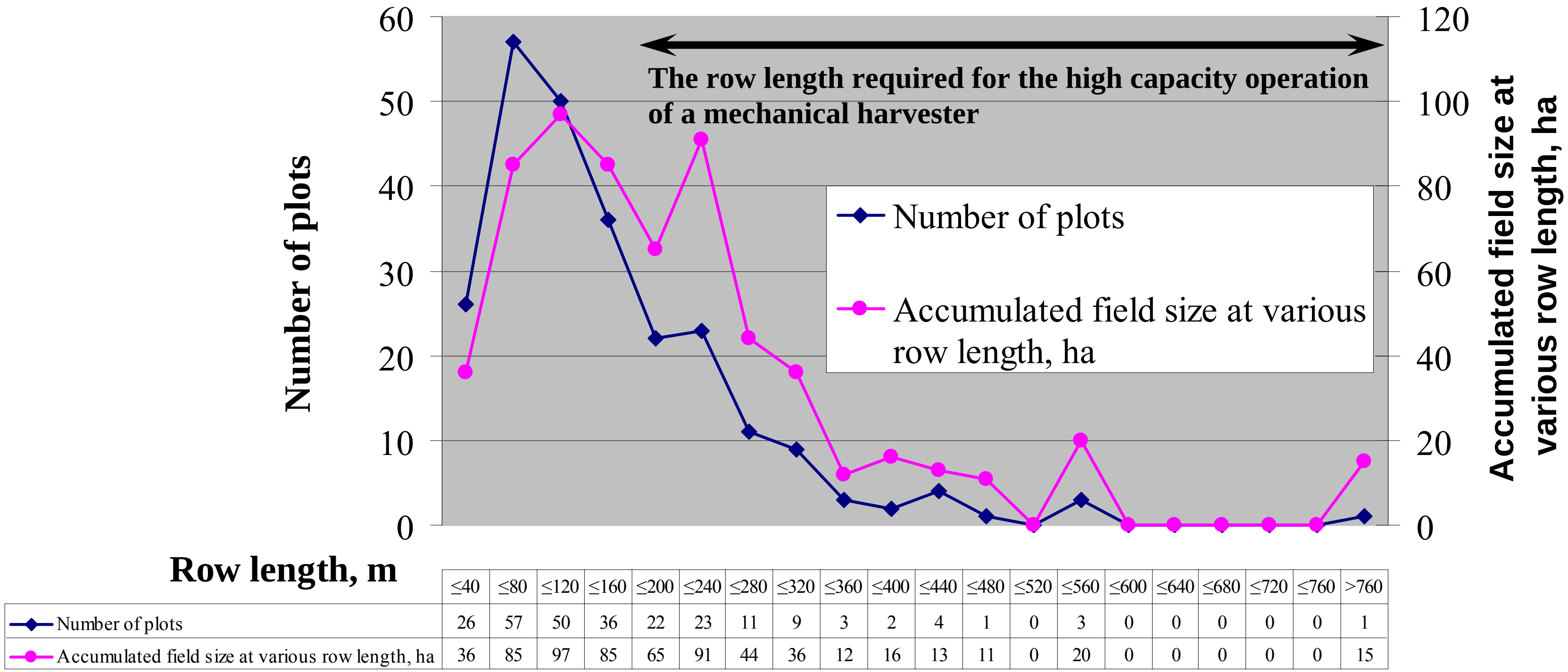
Figure 3.3 Truck loading time by varying the values in row length for given field size

Therefore, high capacity operation of choppers in the study site is feasible, even though plots whose row length is between 40 m and 80 m are common (Figure 3.4). The survey results showed that the accumulated area of fields whose row length is longer than 160 m was approximately 316 ha (or 1,975 rai) or 51% of the total area surveyed.

3.4.3 Influence of the number of trucks on the field capacity of the chopper

In order to examine the influence of the number of trucks on field capacity of the chopper, the number of trucks required for working with the chopper was determined based on the following assumptions:

(1) The amount of working time during a single day is generally assumed to be 12 hours.



	≤40	≤80	≤120	≤160	≤200	≤240	≤280	≤320	≤360	≤400	≤440	≤480	≤520	≤560	≤600	≤640	≤680	≤720	≤760	>760
Number of plots	26	57	50	36	22	23	11	9	3	2	4	1	0	3	0	0	0	0	0	1
Accumulated field size at various row length, ha	36	85	97	85	65	91	44	36	12	16	13	11	0	20	0	0	0	0	0	15

Figure 3.4 Number of plots classified by row length

(2) On a particular day, one chopper is allocated to one field. It could not be moved to operate on other fields during that day. This reflects the customs of this region.

The truck loading time (TLT) and the cumulative time for the truck to return to the field (TRTR) were calculated for each investigated field based on the data acquired by the field investigation. The number of trucks (NTRUCK) required for working with a chopper without the pause time of the chopper waiting for a truck could be determined by the following expression:

$$NTRUCK = \frac{TLT + TRTR}{TLT}, \tag{3.3}$$

where the value of NTRUCK should be rounded to the highest integer.

The chopper's cutting time in one day (CT) in minutes could be determined by using the following expression:

$$CT = NTRUCK \times TLT \times RTRIP, \tag{3.4}$$

where RTRIP is the number of round trips per day that a truck makes. In this calculation, number of round trips was set at twice a day. This assumption is made based on interviews with truck operators at the study site.

The results showed that when the chopper operated on the investigated fields, the average number of trucks (NTRUCK) required for working with the chopper without the pause time of the chopper for waiting trucks was 6 units of 10-wheeled trucks per plot. Plots of between 0.16 and 3.2 ha and having an average transport distance of 10 km to the K factory could be harvested and transported completely in one day by using 6 units of 10-wheeled trucks per plot. The number of plots in this size range was 160.

On the other hand, fields of 1.6 and 14.4 ha in size and 7 km distant from the K factory on average could not be harvested in one day by using 6 trucks. The number of plots in this category was 88.

An average percentage of the chopper's cutting time in relation to the total working time was 50%, when 6 trucks made two round trips a day. The chopper's operation had to be stopped for half a day, though there were still some remaining sugarcane stalks. This shows that the cutting time of the chopper was restricted by the number of trucks and the number of possible round trips. Two possibilities exist for extending the chopper's cutting time per day: (1) increasing the number of trucks per plot and/or (2) increasing the number of round trips on such plots, as expressed in eqn. (3.4).

Figure 3.5 shows influence of the number of trucks on the chopper's field capacity. When a field having a yield of 400 t and having 127 m rows, located 7 km from the sugar factory, was considered, a minimum of 5 trucks (NTRUCK) was needed to eliminate the pause time of the chopper waiting for a truck. The chopper's total cutting time was 326 minutes. This cutting time was 45% of the number of daily working hours. It was found that a greater numbers of trucks allowed the chopper to operate longer in the course of a single day. For example in Fig. 4, when the number of trucks were increased to 11, the cutting time of the chopper would increase to 717 minutes or nearly 100% of the number of working hours per day. This would decrease the amount of time required to complete the harvest of this plot from 3 to 2 days.

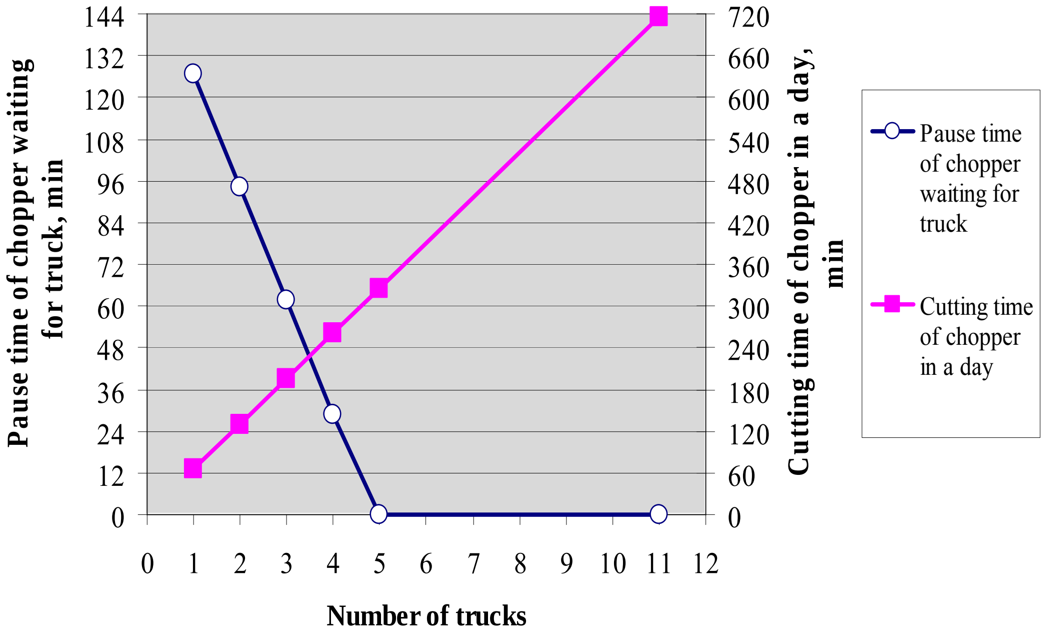


Figure 3.5 The effect of number of trucks on field capacity of the chopper (When a field having a yield of 400 t and having 127 m rows, located 7 km from the sugar factory was considered)

3.5 Discussion

The results obtained in the previous subsection showed that the efficiency of the chopper could be improved by increasing the number of trucks used.

However, when the total process is considered, an increase in the number of trucks will result in an increase in the number of trucks waiting to unload at the sugar factory, and therefore in an increase in waiting time. A longer waiting time will not only lead to a reduction of work efficiency but also to a decrease in the weight and quality of the delivered sugarcane. In addition, it will delay the return of the trucks to fields, and reduce their availability to transport sugarcane to the factory, as well as causing chopper downtime. Thus, an excessive number of trucks in the harvesting and transportation system will decrease the number of possible round trips per day that the trucks can make. The sugarcane purchasing database of the K factory showed that most trucks could transport loads only once a day. The percentage of days in which the trucks transported cane once a day was 72% of their total delivery days, while the percentage of delivery days in which the trucks transported the harvests twice and three times a day was 23%, and 5% respectively. These facts indicate that an increase in the number of trucks was not an effective solution when the improvement in the efficiency of the sugarcane harvesting and transportation system as a whole was considered. Accordingly, how to best utilize the existing availability of trucks within the surveyed region is of importance. Proper determination of the optimum truck number needed for the sugarcane fields is necessary to support the efficient use of the chopper. Thus, the effective allocation of trucks for improving the efficiency of the sugarcane harvesting and transportation system should be considered a significant issue for further research.

However, truck allocation for sugarcane harvesting and transportation in Thailand is complicated by the facts that field size of sugarcane cultivation in Thailand is commonly small as well as by the ownership structure of the sugar industry. Large differences exist between the Thai sugar industry and those of other sugar exporting countries. As our field investigation found, the average size of the sugarcane plots in the study site was 2.5 ha. Also, there is separate ownership of each sector of the Thai sugar industry including growing, harvesting and transporting, and mill processing. Only 3% of the sugarcane farmers in the study site own their own farms and mechanical harvesters. In contrast, in Australia and South Africa, sugarcane farms and mechanical harvesters are privately owned and average between 20 and 200 ha in size. In Brazil and the United States, most land under sugarcane cultivation is owned or controlled by the sugar factory (Higgins et al., 2007). These facts make truck allocation for efficient sugarcane harvesting and transportation in Thailand more difficult to achieve than in other countries.

As described, in Thailand three groups are involved in the harvesting and transportation processes: sugarcane farmers, the owners of mechanized resources, and the sugar factories. Each has his own needs regarding these processes. Both the owners of mechanized resources and sugarcane farmers would like to minimize the number of days required to harvest the fields, and the truck owners would also like to minimize the trucks' total traveling distance in order to reduce fuel costs. The sugarcane farmers and sugar factories want to minimize the deterioration time of the harvests. These facts clearly indicate the individual needs of each participant in the chain concerning their quests for further efficiency. Therefore, truck allocation for improving the mechanical harvesting and transportation system in Thailand should be considered together with input from the groups involved. Any solution should consider the social dimensions in order to determine an appropriate profit distribution.

3.6 Summary

A field study was conducted in Udon Thani province, in northeastern Thailand, to accumulate information for analyzing the system's current shortcomings. The accumulated information showed that mechanical harvesting is key for reducing harvesting cost by around 8 to 57 US$ per ha, when compared with manual harvesting in the case of burned and green cutting, respectively. In addition, analyses performed through the use of a simple sugarcane harvesting and transportation simulation based on data obtained by time studies of the harvesting and transportation operations indicated that the field capacity of a chopper-type mechanical sugarcane harvester depends on the condition of the field in which it works, and the number of accompanying trucks it requires. Though the sizes of the fields in this area are relatively small, the accumulated area of fields having row lengths of longer than 160 m which allows the effective usage of a chopper was 316 ha or 51% of the total field area in this region. This fact shows that chopper can work at high capacity in half of the sugarcane fields in this region. However, the limited availability of trucks significantly influences the efficiency of mechanical sugarcane harvesting and transportation. In addition, since truck allocation affects the profit distribution among the various groups engaged in sugarcane production (i.e., sugarcane factories, machinery owners, and farmers) a truck allocation plan should be devised based on input from these groups.

Chapter 4

Truck allocation planning for cost reduction of mechanical sugarcane harvesting in Thailand

4.1 Introduction

Mechanical sugarcane harvesting has been considered to be the key to reducing the cost of harvesting. Its operations, especially in green sugarcane harvesting, would increase farmers' income and also provide environmental benefits. However, given that sugarcane fields in Thailand are relatively small compared with those in other sugarcane producing countries, the effective management and allocation of mechanical harvesters and trucks to many small fields is required to improve the operational efficiency of harvesting and transportation, as discussed in our previous paper (Kaewtrakulpong et al., 2008).

In Thailand, chopper type mechanical sugarcane harvesters are widespread. This type of harvester usually operates with some trucks. Sugarcane stalks are cut into 12-14-inch billets and loading, by using loading elevator mounted on the chopper, into truck that runs keeping its orientation parallel with the chopper. When sufficient numbers of trucks are available, the chopper can carry out continuous harvest operation. However, there are not enough trucks in the surveyed region to cover the transportation needs. Hence, effective allocation planning of mechanical sugarcane harvesters and trucks is vital. By determining the optimum number of trucks needed for the sugarcane fields, it is possible to make efficient use of mechanical sugarcane harvesters.

Few studies on truck allocation planning for Thai sugarcane production have reflected local constraints in sugarcane cultivation, which differ from other sugar exporting countries. Singh and Abeygoonawardana (1982) and Singh and Pathak (1994) developed computer programs to simulate mechanical harvesting and transporting in Thailand. The programs determined the number of trucks needed to transport the sugarcane harvested by a harvester in a field at certain distance from a sugar factory, and then calculated the operating cost of mechanical harvesting. However, the model embedded in these systems considered only one mechanical harvester working with multiple trucks. Chamnanhlaw et al. (2004) developed two algorithms by applying the genetic algorithm to allocate the trucks for sugarcane delivery from the fields to a sugar factory through one harvesting season. Their algorithms did not allocate the trucks to each field directly, but to a group of fields. In addition, their algorithms did not consider the field capacity of a mechanical sugarcane harvester, despite the fact that the need of elapsed time for harvesting and delivering of each field is usually unequal due to variations in the field characteristics and distance to the sugar factory.

In this study, we present the planning process required for the allocation of multiple mechanical harvesters and trucks to multiple fields. The objectives of this study are cost reduction by suitable allocation of mechanical harvesters and trucks, to improve the operational efficiency of mechanical harvesting, and to enable the appropriate distribution of profits to the groups concerned.

Our previous study found that there are three groups involved: sugarcane farmers, the owners of mechanized resources, and sugar factories. The problem of harvesting and transportation is crucial for all three. As well, they each have their own needs in the harvesting and transportation processes. Both the owners of mechanized resources and sugarcane farmers would like to minimize the number of operating days required to harvest the fields, and the owners of trucks would also like to minimize the total traveling distance of trucks to reduce fuel costs. The sugarcane farmers and sugar factory want to minimize deterioration time of the harvests.

Although efficiency in harvesting and transportation can be improved by optimizing one objective function, the result obtained by considering only one group's needs would conflict with the aims of the other groups, and thus the solution obtained would become unacceptable. Thus, a mechanized resources allocation plan for improvement of the operational efficiency of mechanical harvesting and the transportation system should be considered together with acceptance of the plan gained from the engaged groups. None of the previous studies have considered compromise planning in this kind of environment for mechanized resources allocation in sugarcane harvesting and transportation. Thus, in this study, both operational efficiency and the appropriate distribution of profit were considered through multi-objectives planning reflecting the desires of all groups.

4.2 Data sources and simulation

4.2.1 Survey methods

In the previous chapter, the results of field surveys, time studies, and interviews were reported. The first field survey was performed from August through December, 2005. Field size, field shape, distance to a sugar factory, and geographical location of each sugarcane plot were measured and collected. Time studies of the operation of mechanical harvesters and trucks were carried out in December, 2005. It is very commonly observed that trucks form long waiting queues in front of a sugar factory. When a truck's turn comes, the truck proceeds to the reception area for inspection of the quantity and quality of the sugarcane delivered, and then the harvest is unloaded. The interviews of the operators of mechanical sugarcane harvesters and truck drivers were also conducted.

4.2.2 Simulation of mechanical sugarcane harvesting and transportation

The results of the time studies and surveyed data of trucks have been listed in

Table 3.5(a) and 3.4(b), respectively. Field characteristics, such as field size, row length, amount of sugarcane, and distance to the sugar factory were also used as inputs of the mechanical sugarcane harvesting and transportation simulation introduced below. This simple simulation that partly reported in the previous paper calculates the parameters for calculation of the transported amount of sugarcane by use of a single truck, or a truck and trailer pair from a certain field. These parameters are comprised of the truck loading time, the cumulative time for the truck to arrive at the field, and the time after harvesting; i.e., the deterioration time of the harvested sugarcane, which are explained as follows.

The truck loading time (TLT) is the time in minutes required to fill one truck. It has been expressed by eqn. (3.1).

A round trip time involves the travel time from the field to the factory and the return time, as well as the amount of time the truck waits in a queue at the factory, and the time for reception and unloading of sugarcane at the factory. The cumulative time for a truck to return to the field, TRTR, has been given by eqn. (3.2).

The TRTR can be rewritten with the summation of TGO, TFACT, and TBACK; these terms can be defined as follows.

$$TGO = \left(\frac{DMF}{ASF} \right) \times 60 + \left(\frac{DPT + BDT}{2} \right) \tag{4.1}$$

$$TFACT = WTM + TRO \tag{4.2}$$

$$TBACK = \left(\frac{DMF}{ASE}\right) \times 60 + \left(\frac{DPT + BDT}{2}\right), \tag{4.3}$$

where TGO is the time consumed delivering the sugarcane from the field to the sugar factory, min; TFACT is the time consumed by the truck at the sugar factory, min; TBACK is the return trip time of the truck from the sugar factory to the field, min; DMF is the distance from the field to the sugar factory, km; ASF is the average traveling speed of a loaded truck, km/h; ASE is the average traveling speed of an empty truck, km/h; DPT is the driver's personal time per truck per round trip, min; BDT is the time spent on refueling of the truck per round trip, min; WTM is the waiting time of the truck in queue at a sugar factory, min, and TRO is the time for reception and unloading operations at a sugar factory in minutes. This term is composed of the waiting time required to weigh a truck loaded with delivered sugarcane, the sampling test to determine the quality of the delivered sugarcane, the unloading time, and the time required to weigh an empty truck.

Prior to transport, it was found that delays occurred when loaded sugarcane had to be adjusted in a truck. Therefore, TAD, the time consumed approximately 5 and 10 minutes for adjustment of the harvested sugarcane in the truck and a trailer, respectively, was added.

After harvesting, a loss in the quality of the sugarcane occurs. The time involved in deterioration of the harvests (DT) could be estimated by the summation of the time for sugarcane adjustment in the truck, the time for delivering the sugarcane from the field to the sugar factory, and the time that the truck spends at a sugar factory until unloading of the sugarcane is completed. Thus, DT in minutes could be expressed by:

$$DT = TAD + TGO + (TFACT - 5) \tag{4.4}$$

In this formula, the time for weighing the empty truck, around 5 minutes, was subtracted from the time the truck spends at the sugar factory to represent the time that the quality of the sugarcane deteriorates while the truck is waiting at the sugar factory.

Thus, the truck loading time, the cumulative time for the truck to arrive at the field, and the deterioration time of the harvested sugarcane could be calculated by using this simulation. The number of round trips in a day was calculated by dividing working hours per day by the time spent for one round trip. The time spent for one round trip is summation of the truck loading time and the cumulative time for the truck to arrive at the field. Calculated number of round trip is denoted by STRIP for a 10-wheeled truck and by LTRIP for a 10-wheeled truck with a trailer. Since the values of STRIP and LTRIP must be integer numbers, the nearest integer number was used. This means the working hour became longer than the previously determined hours; i.e. 12 hours. Then the amount of delivered sugarcane per day by a 10-wheeled truck (SD), and that by a 10-wheeled truck with a trailer (LD) can be obtained by multiplying STRIP and LTRIP by the loading capacity of 10-wheeled truck, and of 10-wheeled truck with trailer, respectively. These values (STRIP, LTRIP, SD, and LD) were used in optimization of the allocation plans. The development of the allocation plans is described in the next section.

4.3 Application of multi-objective optimization to allocate mechanized resources

4.3.1 Development of allocation plans

In this study, three objective functions reflecting the considerations of the owners of mechanical harvesters and trucks, sugarcane farmers, and sugar factories were defined based on integer programming. The number of 10-wheeled trucks and 10-wheeled trucks with trailers allocated in fields i, ST_i and LT_i respectively, are defined as the decision variables of the allocation plans. The three objective functions are explained as follows.

(1) Objective function 1 (f_1): Minimize number of operating days

Owners of mechanized resources and sugarcane farmers need to minimize the number of harvesting and transportation days. They want to complete their operations as quickly as possible. If the harvesting and transportation processes can be accomplished in a shorter period of time, the owners of mechanized resources can begin operations on fields waiting for harvest. Post-harvest operations, such as land preparation for the next crop, can also be begun earlier.

The following assumptions were made in the development of the truck allocation plans, in order to make the plans as simple and realistic as possible:

(1) The working hours a day is assumed to be 12 hours basically.

(2) One mechanical sugarcane harvester is allocated to one field. It could not move to operate on further fields on that day. This reflects the custom in this region.

Therefore, minimization of number of operating days can be expressed as

$$Minimize \sum_{i=1}^{h} \frac{Y_i}{(ST_i \times SD_i + LT_i \times LD_i)}$$

where h is the number of mechanical harvesters, unit; Y_i is the yield of the field i in which a harvester operates, t; ST_i is the number of 10-wheeled trucks working with a harvester operating on the field i, unit; LT_i is the number of 10-wheeled trucks with trailers worked with a harvester operating on the field I, unit; SD_i is the amount of delivered sugarcane per day of a 10-wheeled truck working with a harvester operating on the field i, t, and LD_i is the amount of delivered sugarcane per day of a trailer worked with a harvester operating on the field i, t.

The numbers of trucks for each truck type (ST_i and LT_i) assigned to field i are values to determine. Once ST_i and LT_i are determined, the daily amount of harvested sugarcanes can be transported by the assigned trucks can be given by the denominator of the above expression. Since yield of the field i is given, number of operating days for completing the harvesting and transportation operations in all fields can be obtained.

The objective function is usually constrained by the availability of mechanized resources. The available number of mechanical harvesters, 10-wheeled trucks, and 10-wheeled trucks with trailers available in the area determined by the field survey are shown in Table 4.1. In addition, the objective function is also subjected to the daily milling capacity of the factory. The milling capacity of the K sugar factory, one of the factories located in our study site, was investigated. Its total daily milling capacity was 10,211 t of sugarcane (Office of the cane and sugar board, 2006).

During harvest season from November or December to ends in March or April, the percentage of sugarcane harvested by mechanical harvesters varies in the range from 10% to 22% of the total daily milling capacity. To make the simulation more realistic, the set of constraints expressed by the following equations are added.

$$\sum_{i=1}^{h} ST_i \leq \textit{Numbers of 10-wheeled trucks available for transporting the harvests}$$

$$\sum_{i=1}^{h} LT_i \leq \textit{Numbers of 10-wheeled trucks with trailers available for transporting the harvests}$$

$\sum_{i=1}^{h}(SD_i + LD_i) \leq$ *Maximum of daily amount of mechanical harvested sugarcanes supplied to the sugar factory*

$\sum_{i=1}^{h}(SD_i + LD_i) \geq$ *Minimum of daily amount of mechanical harvested sugarcanes supplied to the sugar factory*

Table 4.1 Data used in the allocation plan as the constraints

The availability of mechanized resources in our study area	Value
Number of mechanical harvesters, unit	6
Number of 10-wheeled trucks, unit	38
Number of 10-wheeled trucks with trailer, unit	8

(2) Objective function 2 (f_2): Minimize total traveling distance of trucks

The total traveling distance of trucks from the sugarcane fields to the sugar factory should be minimized because this dimension directly increases the transportation costs. Minimizing the distance is crucial due to the current high price of fuel. Thus, truck owners would like to minimize the total traveling distance of their trucks. Minimization of the total traveling distance of trucks can be formulated as an equation given by

$$Minimize \sum_{i=1}^{h}(ST_i \times STRIP_i + LT_i \times LTRIP_i) \times DAY_i \times DIS_i \times 2$$

where $STRIP_i$ is the number of round trips per day of a 10-wheeled truck worked with a harvester operating on the field i; $LTRIP_i$ is the number of round trips per day of the trailer worked with a harvester operating on the field i operating on field i; DAY_i is the number of operating days of a harvester operating on the field i, and DIS_i is the distance from the field i to the factory, km.

This minimized objective function has the same constraints as the previous objective function.

(3) Objective function 3 (f_3): Minimize deterioration time of the harvested sugarcanes

Sugarcane starts deterioration soon after harvest. Loss in sugarcane quality come from deterioration is vital. The income of sugarcane farmers depends on the amount and quality of harvested sugarcane. Their harvests are priced when the trucks arrive at the sugar factory. Thus, the deterioration time of the harvested sugarcane should be minimized to develop an economical allocation plan of mechanized resources. If this time is long, the loss in the weight and quality of the harvested sugarcane will increase (Rungrat et al, 2000). This will result in a decrease in the income of sugarcane farmers. In addition, deterioration of the harvest is related to the opportunity cost of the sugar factory. This leads to a reduction in the amount of sugar produced and thus in the income of the sugar factory. Deterioration of the harvest detrimentally affects milling efficiency. *Leuconostoc mesenteroides* lactic acid bacterial infections mostly occur when harvest-to-crush times are delayed. Dextran, a high viscosity glucopolysaccharide, produced by such bacteria can reduce evaporation and crystallization rates (Eggleston and Harper, 2006).

Minimization deterioration time of the harvested sugarcanes is thus one objective in this study, because sugarcane farmers and sugar factories both want to maximize their profitability and productivity. Minimization of this objective function can be formulated as

$$Minimize\sum_{i=1}^{h}(ST_i \times SDT_i \times STRIP_i \times DAY_i) + (LT_i \times LDT_i \times LTRIP_i \times DAY_i)$$

where SC_i is the capacity of a 10-wheeled truck worked with a harvester operating on the field i, t; LC_i is the capacity of a trailer worked with a harvester operating on the field i, t; SDT_i is the deterioration time of the sugarcane transported by a 10-wheeled truck worked with a harvester operating on the field i, min, and LDT_i is the deterioration time of sugarcane transported by a trailer worked with a harvester operating on the field i, min.

The constraints of this minimized objective function are the same set of constraints as the previous.

4.3.2 Formulation of multi-objective optimization (MOO) problem

The proposed objective functions reflecting the considerations mentioned above tend to be competitive with each other. The results obtained from individual optimization of each objective function usually conflict with each other (which will be discussed in Section 4.5). To find a compromise solution, optimization of all objective functions simultaneously is needed.

Francisco and Ali (2006) and Piech and Rehman (1993) used MOO to solve the problem of resources allocation and farm planning, respectively. Their results demonstrated that MOO was more appropriate than single-objective optimization (SOO) for generating solutions to the multi-criteria decision-making problem. Thus, in order to obtain a compromise solution for the mechanized resources allocation in sugarcane harvesting and transportation, MOO should be used.

4.3.3 Solution method of MOO problem

In this study, the minimum deviation method, one solution method of MOO, was used to find the preferred compromise solution. This method minimizes the sum of individual objectives' fractional deviations obtained from individual optimum values. The fractional deviation of an objective refers to the ratio of the deviation of a value of that objective from its individual optimal solution and its maximum deviation. The maximum deviation of an objective is obtained from the difference between its individual optimal solution and its least desirable solution, which would correspond to the individual optimal solution of one of the other objectives (Tapan, 1999). The general statement of programming with k objective functions is given as follows:

$$\text{Minimize} \quad F = \sum_{n=1}^{k} w_n \left[\frac{f_n\left(ST_i^*, LT_i^*\right) - f_n\left(ST_i, LT_i\right)}{f_n\left(ST_i^*, LT_i^*\right)} \right]$$

where $f_n\left(ST_i^*, LT_i^*\right)$ is the value of objective function n at its individual optimum ST^* and LT^*; $f_n\left(ST_i, LT_i\right)$ is the function itself, and w_n indicates the relative importance that the decision maker attaches to objective function n which must be specified for each of the k objective functions.

In our study, we set w_n for each objective function to equal 1, because each participant involved in the sugarcane harvesting and transportation process is equally important.

4.4 Computational experiment

A computational experiment was repeated five times to check the performance of MOO for mechanized resources allocation. An area of 10 km by 10 km, covering 248 sugarcane fields, around the K factory was investigated to use in our computational experiment. All investigated fields were classified into nine datasets depending on their field size (3 levels) and distance to the factory (3 levels), as shown the number of plots in each dataset and the criteria of each dataset in Table 4.2.

The randomly selected fields of 9 datasets were used in a computational experiment. The number of fields taken from each dataset equaled the number of mechanical harvesters working in the region. According to our surveyed data, the number of mechanical harvesters working in our study site was 6. The field characteristics of every random selected field were put into the simulation models to calculate the parameters affecting the performance of harvesting and the transportation processes. Then the numbers of round trips per day of each truck type, and the amount of harvested sugarcane in one day were determined, as described in Section 4.2.

All obtained values for each dataset were used simultaneously to perform SOO and MOO based on the proposed objective functions and the minimum deviation method respectively. Afterwards, the sets of the number of trucks allocated to fields corresponding to SOO and MOO were obtained.

Table 4.2 Number of plots at various field sizes and distances to the K factory

Field size, ha	Distance to sugar factory, km			Total
	≤5	5<Distance≤10	>10	
≤ 1.6	16 (Set 1)	57 (Set 4)	55 (Set 7)	128
1.6<Field size≤3.2	26 (Set 2)	32 (Set 5)	14 (Set 8)	72
>3.2	12 (Set 3)	25 (Set 6)	11 (Set 9)	48
Total	54	114	80	248

In order to compare the outputs of mechanized resource allocation obtained from SOO and MOO, the operating costs, such as the cost of hiring the operators of the mechanical harvesters and truck drivers, the fuel cost of the mechanical harvesters and trucks, and the loss of earnings caused by post-harvest deterioration were calculated by using the surveyed and secondary data as shown in Table 4.3. The cost of each working group engaged in these processes was acquired in this way.

Analysis of variance (ANOVA) was also used to clarify the factors affecting the sugarcane harvesting and transportation costs of the sugarcane farmers, the owners of machinery, and the sugar factory. In addition, a comparison between the output of MOO and the output of the currently used truck allocation plan was made to check the usefulness of MOO. Based on the interviews of truck operators at the study site, the assumption of the currently used truck allocation plan in this study was determined by setting the numbers of round trips of each truck type as twice a day.

4.5 Results

4.5.1 Comparison between SOO and MOO

The operating costs of each group in every set are displayed in Table 4.4. The minimum cost of each set was stressed by formatting the figures in bold.

(1) Minimizing deterioration time of the harvested sugarcanes was not an equitable plan

Table 4.3 Data used in the computational experiment for calculating the costs

Item	Value	Unit	References
Fuel consumption of mechanical harvester	0.68	L/min	From survey
Hired cost of mechanical harvester for cutting	85	baht[†]/t of sugarcane	From survey
Fuel consumption of 10-wheeled truck	0.25	L/km	From survey
Fuel consumption of 10-wheeled truck with trailer	0.33	L/km	From survey
Wage rate	139	baht/d per capita	From www.mol.go.th
Fuel price	23.49	baht/L	From www.eppo.go.th
Price of sugarcane	668.17	baht/t	From www.ocsb.go.th
Price of sugar	11.17	baht/kg	From www.ocsb.go.th
Weight loss rate of harvested green sugarcane	0.0171	t/d	Rungrat et al. (2000)
Rate of reduced sugar of harvested green sugarcane	0.0068	t of sugar/d	Rungrat et al. (2000)

[†] Currency unit of Thai, and 1 US$ equals 36 baht.

When the number of trucks was allocated to fields by using the minimized deterioration time of the harvested sugarcanes as an objective function, this allocation plan was a favorable plan for sugarcane farmers and sugar factories because the cost to the sugarcane farmers and sugar factories in every dataset were minimal when compared with other plans, as shown in Table 4.4(a) and 4.4(b). However, this allocation plan was not an equitable plan, because it gives sugarcane farmers and sugar factories an advantage over machinery owners. If this plan was to be used, the machinery owner would have to pay more money for fuel costs due to increases in the total travel distance. This increased portion would cause the cost to the machinery owner to be at a maximum when compared with the other plans, as shown in Table 4.4(c).

In addition, by minimizing the deterioration time of the harvested sugarcanes does not make the plan a suitable one from an economic viewpoint. Table 4.5 can be used as one example supporting this conclusion that the money, around 92 US$, or 3,310 baht (1 US$ equals 36 baht) was required due to the increase in the total traveling distance. But the increased incomes of the sugarcane farmers and of the sugar factory were less than the additional money. The increased income of the sugarcane farmers was only 1.9 US$ (or 67 baht), and was 12.4 US$ (or 447 baht) for the sugar factory.

Table 4.4 Average cost of each group that occurred when the mechanized resources were allocated by using the individual single-objective optimization and MOO model

(a) The average cost to the sugarcane farmer, baht[†]/t

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
Min Operating day	85.62	85.63	85.62	85.65	85.66	85.65	85.71	85.71	85.67
Min Total traveling distance	85.63	85.64	85.64	85.67	85.66	85.66	85.73	85.72	85.69
Min Deterioration time	**85.61**	**85.61**	**85.61**	**85.64**	**85.63**	**85.64**	**85.69**	**85.69**	**85.66**
MOO model	85.64	85.63	85.63	85.66	85.66	85.66	85.72	85.72	85.68

(b) The average cost to the sugar factory, baht/t

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
Min Operating day	5.00	5.07	5.02	5.22	5.27	5.22	5.71	5.69	5.41
Min Total traveling distance	5.10	5.15	5.10	5.39	5.32	5.28	5.82	5.80	5.55
Min Deterioration time	**4.88**	**4.90**	**4.92**	**5.15**	**5.08**	**5.13**	**5.58**	**5.52**	**5.33**
MOO model	5.12	5.09	5.04	5.32	5.29	5.26	5.80	5.78	5.45

(c) The average operating cost to the owner of mechanical harvesters and trucks, baht/t

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
Min Operating day	46.89	**46.77**	38.23	60.32	**46.59**	**43.15**	67.84	50.21	45.80
Min Total traveling distance	46.94	47.38	**37.83**	**59.44**	47.38	43.80	**66.56**	49.84	**44.39**
Min Deterioration time	47.39	49.32	38.74	60.75	49.13	44.63	69.80	52.88	46.12
MOO model	**46.66**	46.99	38.55	59.52	46.68	**43.15**	66.68	**49.54**	45.71

[†] Currency unit of Thai, and 1 US$ equals 36 baht.

(2) Minimizing the total traveling distance of the trucks resulted in more operating days than usual

Although the operating costs for the machinery owners in some datasets were minimum by using the individual minimized objective functions, this minimization did not ensure that an acceptable solution could be obtained. For example, the minimized total traveling distance objective function seemed to be a good plan in Set 3, Set 4, Set 7 and Set 9. However, the adequate plan should not be considered by using the cost only, but the completion time was also necessary to be considered. Table 4.5 shows one example of the results obtained from the computational experiment in Set 9, where by using the minimized total traveling distance as the truck allocation plan, the cost to the machinery owner was about 1.19 US$ (or 43 baht) per t. This cost slightly differed when compared with the operating cost obtained from the compromise solution, 1.22 US$ (or 44 baht) per t. However, a significant difference was observed in the number of working days. When the total travel distance was shortened, 5.36 days were required, whereas in the compromise solution, 1.67 days were required. This difference in the number of working days required to bring the sugarcane to the factory was unacceptable, especially for sugarcane farmers waiting for harvest to occur. This difference would cause them to lose the opportunity to obtain a better price, because their fields would possibly be harvested late or delayed the chance of harvesting the sugarcane when its sugar content is high. The sugar factory would also lose sugar productivity due to this delay. Moreover, the harvesting season would be extended, and preparation of the next crop therefore postponed. This is one evidence showing that minimization of each objective function individually may result in an unacceptable solution.

(3) Minimized number of operating days used more mechanized resources

The minimum of the operating cost for the machinery owner in Set 2 and Set 5 occurred by using the minimization number of operating days as an objective function for truck allocation. When compared with the results obtained from the MOO of both sets, it was found that the difference in cost was very small (Table 4.4(c)). In addition, the number of working days per unit area obtained from minimizing the number of operating days was equal to the result obtained from MOO, with both of them were minimum (Table 4.6). These results indicated that the smaller amount of money reduced by using the minimization number of operating days does not result in more profit for every group involved. Because there was no significant difference in the number of working days per unit area between minimization operating days and MOO, it could be concluded that the allocation of trucks to fields in Set 2 and Set 5 could attain the minimized value in operating cost and working days by using either the minimization operating days or MOO.

However, when the number of trucks allocated to fields was considered, the total number of trucks allocated by the minimization number of operating days was larger than the total number of trucks allocated by MOO (Table 4.6). Thus, the truck allocation plan by using minimization of the number of operating days sometimes would be inappropriate in regions where the number of available trucks is limited, especially the number of 10-wheeled trucks.

Table 4.5 Result of individual single-objective optimization and compromise solution from computational experiment on Set 9

	Single-objective optimization						Multi-objective optimization	
	Minimize Operating day		Minimize Total traveling distance		Minimize Deterioration time		Compromise solution	
Truck type	ST	LT	ST	LT	ST	LT	ST	LT
Total number of trucks allocated, unit	28	8	18	8	34	0	27	8
Operating day, day	1.67		5.36		2.22		1.67	
Total traveling distance, km	4,811.97		3,362.59		5,172.00		4,328.44	
Total cost of fuel, baht[††]	143,377.28		138,701.02		145,807.09		142,496.96	
Weight loss of green harvested sugarcane, t	4.07		4.20		4.00		4.10	
Amount of reduced sugar, t	1.62		1.67		1.59		1.63	
The cost to the owner of harvester and truck, baht/t	44.40		42.59		45.09		44.07	

[†] Area unit of Thai, and 1 rai equals 0.16 ha or 1,600 m^2.

[††] Currency unit of Thai, and 1 US$ equals 36 baht.

Table 4.6 Number of trucks allocated to fields and number of working days per unit area

	Minimized operating days			MOO		
	Number of trucks, unit		Number of working days[†] per unit area, day(s) per rai[††]	Number of trucks, unit		Number of working days[†] per unit area, day(s) per rai[††]
Replication	10-wheeled truck	Trailer		10-wheeled truck	Trailer	
1	7[†††] (9)[††††]	6 (7)	0.01 (0.01)	7 (8)	6 (8)	0.01 (0.01)
2	8 (9)	7 (7)	0.01 (0.01)	6 (6)	8 (8)	0.01 (0.01)
3	8 (7)	7 (7)	0.01 (0.01)	7 (5)	8 (8)	0.01 (0.01)
4	9 (8)	7 (8)	0.01 (0.01)	8 (7)	8 (8)	0.01 (0.01)
5	11 (9)	6 (8)	0.01 (0.01)	6 (9)	8 (8)	0.01 (0.01)
Total	43 (42)	33 (37)		34 (35)	38 (40)	

[†] Working hour in one operating day is 12 hours.

[††] Area unit of Thai, and 1 rai equals 0.16 ha or 1,600 m^2.

[†††] Figures given in the table are the results obtained from computational experiment on Set 2

[††††] Figures given in parentheses are the results obtained from computational experiment on Set 5

4.5.2 Factors influencing operating costs during harvest and transportation

An analysis of variance was conducted at the 0.01 significance level. The three factors tested were the distance to the sugar factory, the field size of the sugarcane, and the allocation plan. The results of the analysis of variance indicated that for the cost to the machinery owner, two of three factors, the distance to the sugar factory and sugarcane field size, were found to be significant. Meanwhile, the influences of all three factors are significant to the costs to the sugarcane farmers and the sugar factory. In addition, the interaction effect between the distance to the sugar factory and the sugarcane field size have an impact on the operating costs of every group involved in sugarcane harvesting and transportation.

Accordingly, it was confirmed that the cost of harvesting and transportation will increase when a mechanical sugarcane harvester and truck perform in a small field, because of the difficulty involved in working in small field. Worst of all, farmers whose fields were small in size and who had fields located far from the sugar factory were the group that suffered the highest harvesting and transportation costs.

When considering the influential factors investigated in this study that reduce harvesting and transportation costs, the size of fields was the most influential factor affecting the operating costs of mechanical harvesting. Meanwhile, the location of fields was a factor impossible or difficult to change. It is not possible to decrease the distance between fields and the factory. Thus, alternative ways to reduce the costs of sugarcane harvesting and transportation should focus on how to improve the field size of sugarcane plots. One such alternative way will be discussed in the discussion section.

4.5.3 The achievement of cost reduction and efficient operation

When comparing the result of the MOO with the currently used truck allocation plan, it was found that a reduction in the operating cost for the machinery owner was acquired. The percentage of reduction in operating cost was in the range of 4 to 9%. As shown in Table 4.7, the cost could be possibly reduced to the range of 0.06 to 0.14 US$ per t (or 2 to 5 baht/t) by using MOO. In addition, decreasing the working days per unit area could be feasibly achieved by using the MOO approach. The percentage of decrease in the number of working days per unit area was in the range of 4 to 43%.

Furthermore, the operating cost would decrease significantly if the mechanical sugarcane harvesters and trucks operated in fields that are larger than 1.6 ha. As can be seen in Table 4.7, in the case of a sugarcane field located far from the factory, over 5 km, the operating cost of the mechanical harvester performing in this field size was decreased from 1.67 US$ (or 60 baht in Set 4) to 1.31 US$ (or 47 baht in Set 5) per t, and from 1.86 US$ (or 67 baht in Set 7) to 1.39 US$ (or 50 baht in Set 8) per t by using MOO. Similarly, for the field located near the factory, within 5 km, a suitable field size for mechanical harvesting should be more than 1.6 ha (Set 2). Mechanical harvesting in fields less than 1.6 ha (Set 1) should be omitted, even though there was a slight difference in the operating costs in Set 1 and Set 2.

Manual harvesting should be selected to operate in Set 1, because the percentage of decrease in the working days per unit area by using mechanical harvesting in Set 1 was very small (4%) when compared with Set 2 (31%) and other sets. Regarding farm machinery management, a mechanical harvester should be used in other sets for more operational efficiency and more profitability due to the limited number of mechanical harvesters.

4.6 Discussion

This study has attempted to show more proper distribution of the profit among each group engaged in sugarcane harvesting and the transportation process. However, it was found during this study that the owners of mechanized resources were the group that took the most obvious advantage of truck allocation planning over the other groups. A reduction in the operating costs of the owners of mechanized resources was successfully obtained, while the sugarcane farmers and the sugar factory obtained only a shorter working time period in harvesting and transportation. However, this timeliness improvement via truck allocation planning would lead to sugarcane farmers' opportunity to increase the value of their products, if proper selection of the fields to be harvested regarding sugar content, and an adequate schedule for harvesting, are taken into account.

As just mentioned in the previous section, an alternative way to reduce the costs of sugarcane harvesting and transportation could be achieved by increasing field size. Based on our results, the land consolidation approach could be used to reduce the operating cost, especially for sugarcane farmers who have small fields and whose fields are located far from the sugar factory. This approach is feasible, because the possibility of cost reduction in far fields was noticed by the decrease in cost from 1.86 US$ (or 67 baht in Set 7) to 1.39 US$ (or 50 baht in Set 8) and 1.28 US$ (or 46 baht in Set 9) per t, respectively. The decrease in the number of working days was also similarly in a downward trend (Table 4.7(b)). These results highlight that land consolidation, the replacement of holdings consisting of numerous small plots with holdings consisting of a smaller number of larger plots, would lead to the more economical and efficient use of mechanical harvesters and trucks. This kind of further

Table 4.7 Comparison between the current truck allocation plan and MOO model

(a) By considering the operating cost to the machinery owner, baht[†] per t

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
Current plan	50.36	50.10	41.69	61.94	49.85	46.19	70.99	54.28	47.70
MOO model	46.66	46.99	38.55	59.52	46.68	43.15	66.68	49.54	45.71
Cost reduction	3.70	3.11	3.14	2.42	3.17	3.04	4.31	4.74	1.99
% Reduction	7.35	6.21	7.53	3.91	6.36	6.59	6.07	8.73	4.17

(b) By considering the number of working days per rai[††]

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
Current plan	0.0150	0.0141	0.0066	0.0266	0.0121	0.0099	0.0371	0.0168	0.0079
MOO model	0.0145	0.0098	0.0052	0.0186	0.0105	0.0056	0.0316	0.0120	0.0046
% Reduction	3.69	30.55	21.33	30.30	13.56	42.83	14.64	28.60	41.31

[†] Currency unit of Thai, and 1 US$ equals 36 baht.

[††] Area unit of Thai, and 1 rai equals 0.16 ha or 1,600 m^2.

study should be considered carefully to enhance the welfare of sugarcane farmers who have small fields and whose fields are located far from the sugar factory.

4.7 Summary

This study reports application of a multi-objective optimization (MOO) approach for sugarcane production in Thailand. Appropriate usage of mechanical resources has been believed to result in the cost reduction of harvesting and transportation. However, because of limited number of trucks and mechanical harvesters, appropriate allocation of trucks and harvesters is of crucial importance for efficiency of sugarcane harvest. In addition, the allocation of mechanized powers also influences the profits distribution among the three groups involved: sugarcane farmers, the owners of trucks and mechanical harvesters who provide harvesting and transportation services, and sugar factories. These groups usually do not have common interests. Therefore, multi-objective optimization (MOO) was applied in this study to find a compromise solution for the three groups. The parameters used in the MOO model were evaluated by using a simple sugarcane harvesting and transportation simulation derived from the field study in northeastern Thailand. The results showed that the compromise solution obtained from MOO was more acceptable than the solutions obtained from single-objective optimization. The results of analysis of variance indicated that the main factors influencing cost were the distance to a sugar factory, field size, and their interaction. In addition, cost reduction and efficient operation in mechanical harvesting and transportation were achieved in this study. The percentage of reduction in operating cost was in the range of 4 to 9%. The percentage of decrease in the number of working days per unit area was in the range of 4 to 43%.

Chapter 5

Conclusions and recommendations

5.1 Conclusions

Based on this research attempted to reduce the cost of sugarcane harvesting and transportation system in Thailand, and also to improve the efficiency in this system, the following conclusions can be drawn:

1. This study revealed the possibility of the use of mechanical harvesting to reduce the cost of sugarcane harvesting by around 8 US$ per ha when compared with manual harvesting using burned cutting, and 57 US$ per ha in the case of green cutting. As well, the mechanized operation of green sugarcane harvesting will result in an increase in sugarcane farmers' profits, because a higher price for green harvested sugarcane than for burned harvested sugarcane, around 1.58 US$ (or 60 baht) per t, was provided by the OCSB in cooperation with the sugar factory in the study site. These benefits of mechanization could encourage investment in mechanical sugarcane harvesters and/or the expansion of their use in the study site.

2. It was indicated that the field capacity of the chopper depends on the condition of the field in which it performs. The simulation result (Figure 3.3) was consistent with our interview results. In order to allow the chopper to operate effectively, row length should be equal to or longer than 160 m. Thus, high capacity operation of the chopper in the study site is feasible, because the survey results showed that the accumulated area of the fields whose row length is longer than 160 m was 316 ha or 51% of the total surveyed area.

3. The number of trucks on in relation to the chopper's field capacity can increase or decrease the number of operating days required to harvest a field.

However, an excessive number of trucks used in the harvesting and transportation system will cause a decrease in the number of round trips per day that trucks can make.

4. Under the limited mechanized resources of Thai sugarcane harvesting and transportation, the usage of multi-objective optimization (MOO) has demonstrated more proper allocation of mechanized resources to sugarcane fields than single-objective optimization in the aspects of the distribution of operating costs and the operation time. The groups of sugarcane farmers, machinery owners, and the sugar factory could attain these advantages due to the greater value of MOO.

5. Cost reduction and efficient operation in mechanical sugarcane harvesting and transportation in Thailand have been achieved by applying MOO via truck allocation planning. The percentage of reduction in operating cost was in the range of 4 to 9%. The percentage of decrease in the number of working days per unit area was in the range of 4 to 43%. In addition, the factors that are affecting the costs for sugarcane farmers, machinery owners, and sugar factories were clarified.

5.2 Recommendations

From the viewpoint of this research, the following recommendations should be considered:

1. It was found during this study that the owners of mechanized resources were the group that took the most obvious advantage of truck allocation planning over the other groups. A reduction in the operating costs of the owners of mechanized resources was successfully obtained, while the sugarcane farmers and the sugar factory obtained only a shorter working time period in harvesting and transportation. However, this timeliness improvement via truck allocation planning would lead to

sugarcane farmers' opportunity to increase the value of their products, if proper selection of the fields to be harvested regarding sugar content, and an adequate schedule for harvesting, are taken into account. These are issues that should raised and seriously considered in further studies in order to increase total profit among the groups concerned, and to increase the efficiency of supply chain management of the Thai sugar industry.

2. In addition to truck allocation planning, an alternative way to reduce the costs of sugarcane harvesting and transportation could be achieved by increasing field size. Based on the results, the land consolidation approach could be used to reduce the operating costs, especially for sugarcane farmers who have small fields and whose fields are located far from the sugar factory. The results highlight that the land consolidation, the replacement of holdings consisting of numerous small plots with holdings consisting of a smaller number of larger plots, would lead to the more economical and efficient use of mechanical harvesters and trucks. However, the advantages of consolidation must be explained to the sugarcane farmers. In addition, it is necessary to ensure that farmer's post-consolidation holding is the same size as his or her pre-consolidation holding. This kind of further study should be considered carefully to enhance the welfare of sugarcane farmers who have small fields and whose fields are located far from the sugar factory.

3. Because this study focused on the development of more proper truck allocation plan in the specified area, movement between fields to field is rare, the time required to move the mechanized resources from field to field was not considered. However, such time will be taken into account for further study in the topic related to the development of the appropriate schedule for mechanical sugarcane harvesting and transportation.

4. Since the achievements in more proper allocation of compromise planning and its advantages acquired in this study do not require an investment in any mechanized resources and infrastructure, these gains are to be helpful in enhancing and supporting the welfares of the three groups involved in supply chain of the Thai sugar industry: sugarcane farmers, the owners of mechanized resources, and sugar factory. However, the calculations have been conducted depending on the detailed data obtained from the survey in northeastern Thailand. Thus, modification will be needed to become wider applicability.

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Appendix-A

Questionnaire used in the field investigation

General data		
1.	Farmer's name	
2.	Farmer's address Sub-district District Province	
3.	Quota number	
4.	Amount of sugarcane contracted with the K sugar factory, t	
Cultivation data		
5.	Accumulated field size, rai	
6.	Number of sugarcane plots	

Data of each plot		
1.	Plot number	
2.	Plot size, rai	
3.	Plot's address Village Sub-district District Province	
4.	Variety name	

5.	Crop type	○ New planting ○ First stubble ○ Second stubble	Planting date ……………......... Harvesting date ………………. Harvesting date ……………….
6.	Distance to the K sugar factory, km		
7.	Type of water source	○ Rain water ○ Pond, area ………….. rai ○ Well water	
8.	Fertilization	………… time(s) First time: formula ……………………. Second time: formula …………………	

Drawing of an investigated plot

[A drawing of an investigated plot showing plot shape and its geographic information covering latitude, longitude, and altitude]

Appendix-B

Equations for conversion of the GPS positioning data from geodetic coordinates to earth center earth fixed (ECEF) coordinates

In order to determine the row length of the investigated sugarcane fields, the fields' location data acquired by a GPS receiver must be converted from geodetic coordinates to ECEF coordinates (Farrel and Barth, 1999) by using the following equations:

$$x_e = (n_s + h)\cos(\chi)\cos(\varepsilon) \tag{B-1}$$

$$y_e = (n_s + h)\cos(\chi)\sin(\varepsilon) \tag{B-2}$$

where (x_e, y_e, z_e) is the position of the ECEF coordinates; (χ, ε, h) is latitude, longitude, and altitude; e_e is the eccentricity of the earth ellipsoid with a value of 0.0818; n_s is the distance from the surface of the earth ellipsoid to the normal intersection with Z axis in the ECEF coordinates, that is given by

$$n_s(\chi) = \frac{a_e}{\sqrt{1 - {e_e}^2 \sin^2(\chi)}} \tag{B-3}$$

where a_e is the semi-major axis length of the earth with a value of 6378137.0 m.

Appendix-C

Time studies regarding mechanical harvesting and transportation operations

Figure C-1 Turning operation at a headland

Figure C-2 Truck changing operation

Figure C-3 Finishing arrangement of a loading

Figure C-4 Truck fleets in queue at the compound of a sugar factory

Figure C-5 Unloading operation at a sugar factory