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Coconut sap pickup problem with time windows: a case study

[1*]Ongkunaruk, P. and [2]Ongcunaruk, W.

[1]*Department of Agro-Industrial Technology, Faculty of Agro-Industry, Kasetsart University, 50 Ngam Wong Wan Road, Ladyao, Chatuchak , Bangkok, Thailand*
[2]*Department of Electrical and Computer Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, 1518 Pracharat 1 Road, Wongsawang, Bangsue, Bangkok, 10800 Thailand*

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Abstract

The goal of this study is to determine coconut sap pick up routing for a manufacturer who produces coconut sap beverage to avoid coconut sap quality deterioration during the harvest. The pickup up time is suggested to be within four hours after the coconut sap is tapped. Due to the limited pickup time, a vehicle routing problem with time windows is formulated for this coconut sap picking problem. A mixed integer programming approach is then proposed to find the optimal routing solution that minimizes the total cost consisting of the fixed and variable cost of vehicles and the transportation cost. Compared with the current practice, the optimal pickup routing is able to reduce the daily travel distance by 19.4% and the total travel time by 10.76% while the quality of coconut sap is well maintained.

Introduction

Coconut sap is a major raw material to produce coconut products such as coconut beverage, nectar, sugar in Thailand and other countries in Southeast Asia. It can be obtained by tapping the inflorescence of the coconut palm (Atputharajah *et al*.,1986; Xia *et al*., 2011). In Thailand, most Small and Medium-sized Enterprises (SMEs) which use coconut sap as main raw material are confronted with the problem of coconut sap quality deterioration due to sugar fermentation during postharvest, handling, waiting and pickup from farms to factories (Poonpan and Ongkunaruk, 2014). Since coconut sap quality has a huge impact on the quality of all final products, coconut sap pick up should be arranged carefully to maintain the quality of raw material to produce high quality products (Borse *et al*., 2007; Poonpan and Ongkunaruk, 2014). Similar to the Vehicle Routing Problem with Time Windows (VRPTW), this pickup routing problem aims to decide the sequence of delivery or pickup points to be visited by a given delivery vehicle, starting and ending at one or multiple depots with a time window constraint in product pickups (Miller *et al*., 1960; Solomon, 1987, Desrochers *et al.*, 1988; Figliozzi, 2012). Even though the VRPTW is NP-complete, smaller VRPTW problems can be solved by exact methods (Azi *et al.*, 2007; Shanmugam, 2011; Pureza *et al.*, 2012). When the problem size becomes larger, it can be solved by local search (Bent and Hentenryck, 2004), route construction and route improvement heuristics (Figliozzi, 2012), or metaheuristics such as genetic algorithms (Ismail and Irhamah, 2008; Nazif and Lee, 2010), tabu search (Ismail and Irhamah, 2008), ant colony optimization (Ismail and Loh, 2009; Yu *et al.*, 2011; Pureza *et al*., 2012; Tan *et al*., 2012), particle swarm (Kanthavel and Prasad, 2011) and other heuristics (Ismail and Ramli, 2011). If part of the time constraints is allowed to be relaxed, Kumar and Panneerselvam (2012) proposed a variant VRPTW with both hard time and soft time windows, which required a shorter computation time in searching for the best routes.

In Thailand, previous research related to VRPTW has been studied in Ongarj and Ongkunaruk (2013), in which the transportation problem was formulated as an Integer Programming (IP) problem, equivalent to a Bin Packing Problem (BPP) with time window constraints. Their objective was to minimize the number of vehicles used by 3PLs. However, they left the routing problem to the drivers' responsibility. Suwansuksamran and Ongkunaruk (2013) extended the work by Ongarj and Ongkunaruk (2013) by solving a VRPTW instead of a BPP with time windows. They proposed a mixed integer programming to minimize the total cost consisting of the fixed and variable cost of vehicles and transportation cost. They defined a binary parameter to represent whether the customer has a time window constraint and used CPLEX to

*Corresponding author.
Email: *ponthipa.o@ku.ac.th*

solve the problem. The result showed that the MIP VRPTW can reduce total cost and computational time. In addition, Kanjanarat and Ongkunaruk (2014) proposed a coconut harvest planning as a strategic supply planning using integer programming for a medium-sized coconut manufacturer in Thailand.

In this research, we focus on solving the vehicle routing from a coconut sap manufacturer to pick up coconut sap at farms in Thailand where there is a restriction of the delivery time due to quality of sap deterioration by time. The factory is required to pick up the coconut sap from 20-70 farms throughout a year. The coconut sap is a seasonal product and the quality is sensitive to the storage condition. The coconut sap quality remains acceptable up to four hours after harvesting if stored in thermal insulated containers and to eight hours if stored in temperature controlled shipping containers (Poonpan and Ongkunaruk, 2014). Hence, our objective is to schedule vehicles to pick up coconut sap so that the quality of coconut sap was acceptable.

Materials and Methods

The methodology started from collecting the data such as factory and farms' locations, coconut sap quantities during the pickup process including waiting times, handling times, quality checking times and travel times. A regression model was constructed to estimate the handling and quality checking times. The distances among various locations were measured using Google map and verified by the manufacturer. The estimated point-to-point travel times were calculated. Afterwards, we calculated the average coconut sap quantity of each farm from historical data. Once the transportation cost and all necessary parameters were collected, the problem was formulated as a VRPTW problem and solved using IBM ILOG CPLEX version 12.4. If the number of trucks used was less than available number of trucks, then it implied that an optimal solution exists. On the other hand, if the number of trucks used was greater than the available number of trucks, then it implied that the factory could not pick up the coconut sap within four hours. Then, the company should either assign more trucks or temperature- controlled coconut sap after tapping. Finally, the obtained optimal solution was compared with the current practice in terms of transportation cost, total travel time and computational time.

Model formulations

Subscripts and Set

i = Farm index (i=1 is used for the depot location), h, g = Point index, H = A set of locations, k = Truck index, K = A set of vehicles

Parameters

N = The number of locations (farms), M = The number of vehicles, r_k = Coconut sap purchase price per litre, D_{gh} = Distance between points g and h, Q_i = The quantity of coconut sap to be picked up at farm i (litres), C_k = Capacity of vehicle k, F_k = Fixed cost of vehicle k, P_k = Cost per kilometer of vehicle k, T_{ij} = Travel time from i to j (minutes), H_i = The summation of material handling, quality checking and pickup time at farm i and MaxRouteTime = Maximal duration of a single route (in this case 240 minutes)

Decision variables

$$x_{ghk} = \begin{cases} 1 \text{ if point g precedes h with vehicle k} \\ 0 \text{ otherwise} \end{cases}$$

$$y_{ik} = \begin{cases} 1 \text{ if coconut sap of farm i is collected by vehicle k} \\ 0 \text{ otherwise} \end{cases}$$

$$z_k = \begin{cases} 1 \text{ if vehicle k is allocated to pickup coconut sap} \\ 0 \text{ otherwise} \end{cases}$$

$$a_i = \text{departure time from farm i}$$

Mathematical model

Minimize:

$$\sum_{k=1}^{M} F_k \cdot z_k + \sum_{k=1}^{M} r_k \sum_{i=2}^{N+1} Q_i y_{ik} + \sum_{k=1}^{K} \sum_{g=1}^{N+1} \sum_{h=1}^{N+1} P_k \cdot D_{gh} \cdot x_{ghk} \tag{1}$$

Subject to:

$$\sum_{k=1}^{M} \sum_{h=1}^{N+1} x_{ihk} = 1 \qquad \forall\, i \in H, i \neq h \tag{2}$$

$$\sum_{i=2}^{N+1} Q_i \sum_{h=1}^{N+1} x_{ihk} \leq C_k \qquad \forall\, k \in K \tag{3}$$

$$\sum_{i=1}^{N+1} \sum_{j=1, j\neq i}^{N+1} T_{ij} x_{ijk} + \sum_{i=2}^{N+1} H_i Y_k \leq MaxRouteTime \quad \forall k \in K \tag{4}$$

$$\sum_{g=1}^{N+1} x_{hgk} - \sum_{g=1}^{N+1} x_{ghk} = 0 \qquad \forall k \in K, h \in H \tag{5}$$

$$a_g - a_h + N * x_{ghk} \leq N - 1 \quad \forall g, h \in H, g \neq h, g \neq 1, k \in K \tag{6}$$

$$\sum_{i=2}^{N+1} Q_i y_{ik} - C_k z_k \leq 0 \qquad \forall\, k \in K \tag{7}$$

$$\sum_{h=1}^{N+1} x_{ihk} = y_{ik} \qquad \forall i \in H, i \neq h, k \in K \tag{8}$$

Table 1. The comparison of solutions between current method and VRPTW

Method	Current method	VRPTW
Round 1 (R1)	1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18-1	1-18-19-12-14-13-20-21-17-15-16-9-8-7-2-6-4-5-3-22-1
Round 2 (R2)	1-19-20-21-22-23-24-25-26-1	1-23-11-24-26-25-10-1
Total Time (R1/R2) (min)	217/127	231/76

Table 2. The comparison of key performance indicators between current method and VRPTW

Method	Total Distance (km)	Total travel time (min)	Objective Function (baht/day)	Computational Time (sec.)
Current method	85.197	344	3373.031	Depend on driver
VRPTW	68.673	307	3323.459	800 sec[1].
Daily Saving	16.524 (19.40%)	37 (10.76%)	165.24[2]	

[1]The limited time by user

[2]Compared at 10 baht per kilometer

$$\begin{aligned} x_{ghk} &= binary \quad \forall g,h \in H, k \in K \\ y_k &= binary \quad \forall i \in H, k \in K \\ z_k &= binary \quad \forall k \in K \\ a_i &\geq 0 \quad \forall i \in H \end{aligned} \tag{9}$$

The objective function aims to minimize the total cost consisting of the fixed cost of vehicles including a driver wage, purchasing cost of coconut sap, total fuel cost used as in Equation (1). Usually, the company will collect all coconut sap from every farm due to supply shortage. Hence, the purchasing cost can be ignored from the objective function. Equation (2) implies that each sequence of two customers can be allocated to one truck only. Equation (3) implies that the total quantity of products delivered by each truck cannot exceed the truck capacity. Equation (4) implies that the total route time, equal to the sum of the travel time, handling, quality checking and the pickup time, is less than four hours. Equation (5) implies that the vehicle should leave every point entered by the vehicle. Equation (6) represents the sub-tour elimination constraints. Equation (7) links the allocation of customer to a vehicle in use. It implies that if there is an allocation of customer i to vehicle k, then vehicle k must be used. Equation (8) links the allocation and routing components of the VRPTW. Finally, Equation (9) specifies that the decision variables x, y, z are binary variables, and ai is non-negative real number. The problems are solved by an optimization package, IBM ILOG CPLEX version 12.4. The computational time was limited to five minutes.

First, the number of trucks is assumed to be one. If no feasible solution can be found, then the number of truck is increased by one or more to check until an optimal solution can be obtained. This problem will become difficult to solve during high season such as 70 farms. Then, the company would have two choices to solve a problem i.e., either to increase the number of trucks or to control the temperature of coconut sap.

Results and Discussion

Data collection

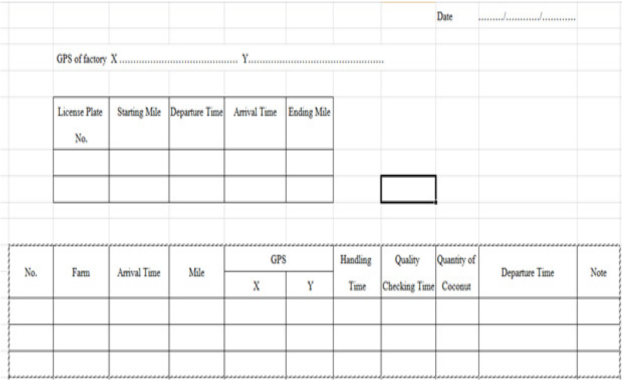
First, we collected data using a form designed for data collection as shown in Figure 1. Then, we used Google map to determine the distance matrix and record the location of farms and factory as shown in Figure 2. Second, we determined the travel time considering two cases: (1) travel time from the factory to every farm and (2) travel time from farm to farm. From historical data, travel time (minutes) from the factory to a farm is equal to the distance *2 (minutes/km), while the travel time (minutes) from farm to farm is equal to distance *3.6 (minutes/km). Next, we calculated the total of material handling, quality checking and pickup time (H_i), which depends on the quantity of coconut sap at farm i (Q_i). Regression models are fitted to the data and the model that maximized R^2 is selected, as shown in Figure 3. The regression equation can be written as follows:

$$H_i = 0.1116 Q_i^{0.7419} \tag{10}$$

Currently, there are 25 farms (N=25) and 3 four-wheel trucks traveling twice a day (then M = 6). We estimate the handling time which includes quality checking, waiting, picking time using the regression model.

Solution comparison

The results showed that the current method still has a room to improve. The proposed MIP solved by IBM ILOG CPLEX version 12.4 was better off. The routes of round 1 and round 2 of the current and MIP models are compared as shown in Table 1. Index value 1 refers to the factory and index values 2-26


Date ..../............/..........

GPS of factory X .... Y...

License Plate No.	Starting Mile	Departure Time	Arrival Time	Ending Mile

No.	Farm	Arrival Time	Mile	GPS		Handling Time	Quality Checking Time	Quantity of Coconut	Departure Time	Note
				X	Y					

Figure 1. The form designed for collecting the data

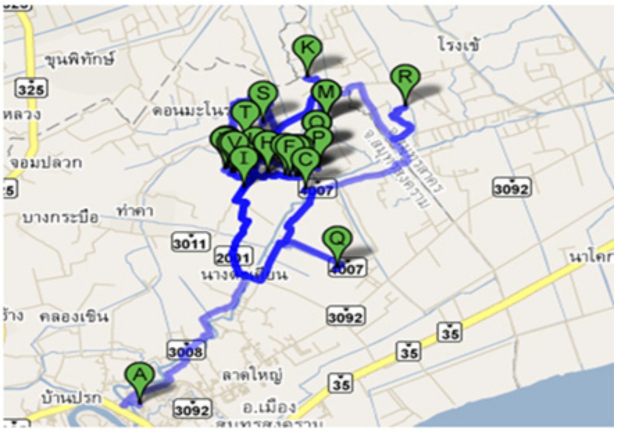


Figure 2. The mapping of coconut farms and manufacturer

refer to farm number 1-25, respectively. Currently, the manufacturer has two trucks and utilizes them without considering time window constraints. During high season, the manufacturer makes an arrangement with farmers to collect coconut saps twice per day. Thus, the pickup time includes two trips in the morning and two trips in the afternoon. In addition, the manufacturer can schedule only one truck to pickup two shifts during low season. However, when the time window constraint is taken into consideration, the optimal solution assigns the truck to pickup coconut saps from farms as long as the total route time does not exceed four hours. Hence, the solution from our proposed method has one longer route and one shorter route resulting in total shorter distances than that of the current method. However, the current solution meets the time window constraints because data used in this research was collected during low season. The proposed method will be more efficient during the high season .

The proposed method led to daily savings in distance of 16.524 kilometres or 19.40%, savings in travel time of 37 minutes per day or 10.76%, and could save about 165.24 baht per day at transportation cost of 10 baht per kilometre as shown in Table 2.

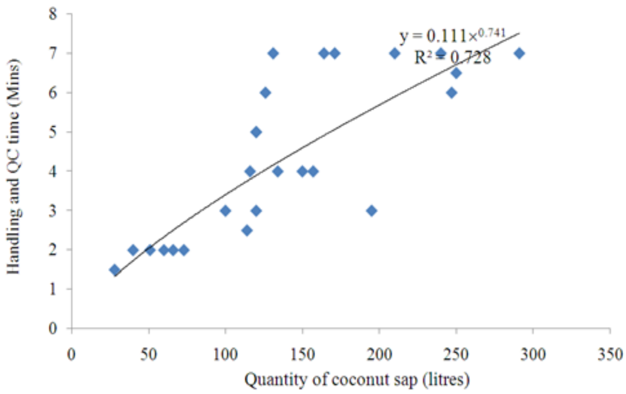


Figure 3. The relationship between handling and quality checking time versus quantity of coconut sap

Conclusion

This research solved the pickup coconut sap problem for a manufacturer who produces coconut sap beverage. This problem is similar to a VRPTW where the coconut sap quality deteriorates by time. From experiments by Poonpan and Ongkunaruk (2014), the pickup time should be within four hours after tapping the coconut sap. Hence, the pickup time after harvesting coconut sap from trees, waiting time and pick up time should not to be over four hours. After formulating and solving the problem as a mixed integer programming to minimize the total cost consisting of the fixed and variable cost of vehicles and transportation cost, the results show that the MIP can reduce the daily distance by 19.40% and the total travel time by 10.76% and still maintain the quality of the coconut sap. Usually, the routing schedule can change due to seasonality of coconut sap production throughout a year. In addition, the handling, waiting, quality checking and picking time are assumed constant in this model so that we could estimate the time matrix. Hence, the actual time would be different and it may affect the total time. When the number of farms is increased, the problem becomes more complex and the use of the proposed method could increase savings , but could require more computational effort.

In the future, the extended research could explore the use of a temperature-controlled truck to relax the time window constraint. In addition, in high season, when the number of farms is large, then the MIP would not be able to solve the problem optimally in a short time. Then, a meta-heuristic algorithm can be studied to solve the problem in real time.

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