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Multi-Compartment Vehicle Loading and Route Optimization: Case for Exporting Thai Fresh Fruits

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Abstract. Multi-compartment vehicles have been currently utilized in fresh fruit transportation because of their ability to consolidate perishable products without mixing them in the same chamber. In addition, each compartment can be set to a specific temperature to prolong the shelf-life of fruits. Nevertheless, the challenge of fruit transportation is to create an optimal route for vehicles, taking both transportation cost and fruit quality into account. The reason is that the quality of fruits has deteriorated when they are transported by the longer time options (which are typically less expensive). Therefore, an optimal vehicle route needs to balance transportation cost and fresh fruit quality. This article has developed a mathematical model for multi-compartment vehicle loading and transportation routing to address such challenges. The model aims to minimize total transportation costs while maintaining the quality of fruits at the destination. The model has been validated using data from fresh fruit exports from Talaad-Thai (Thailand) to Nanning (China). Results indicate that desired quality at the destination directly impacts route decisions and total transportation cost. Meanwhile, the model reduces the number of vehicles required when multi-compartment vehicles are used instead of single-compartment vehicles.

Keywords: multi-compartment vehicle, loading problem, shortest path problem, fresh fruit transportation mixed integer linear programming

1. Introduction

1.1. Fresh fruit transportation

Transportation directly impacts products' quality, especially perishable products. For example, a longer transportation time can negatively affect the freshness of commodities [1] as their qualities deteriorate over time [2]. On the other hand, a fast transportation method typically incurred a high cost of operation. Therefore, effective transportation planning is a key for competitive companies to survive in the modern economy.

Trucks are one of the most common modes of transportation because of their ability to distribute products to the closest final destination [3]. The challenge is the route selection because of the dependency on other factors. For example, in the case of perishable commodities (e.g., fresh fruits), operating cost, transportation time, and product shelf-life are essential factors influencing the route options. Hence, various research has been conducted to develop effective transportation management to minimize the total operation cost of delivering fresh fruits [4].

The effective transportation management also involves an optimal route for trucks. In general, the route selection approaches are primarily based on shortest path algorithms, which intend to lower the cost of travel from one point to another. The shortest path problem has been applied to many applications based on different decision criteria such as time, cost, and distance. Dijkstra's method is a well-known algorithm to find the optimal path. The algorithm enables calculating all shortest paths from a single point to all other points in a network [5]. Dijkstra's algorithm begins with searching the nearest node from the source node that is connecting to the source node during the first iteration. In the second iteration, it finds the next node that is closest to the current node. The node must be a neighbor of the current node or the nearest node discovered for the next iteration. The iteration will end when the n^{th} finds the first n nodes closest to the source node [6].

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1.2. Multi-compartment vehicles

In terms of vehicles, refrigerated vehicles with multi-compartment have been widely used in transporting fresh fruits to keep the products at their optimal temperature. Multi-compartment vehicles were initially used in gasoline supply chain networks but are now used for perishable product distribution and grocery delivery [7]. Due to its separated loading area, consolidating different product segments within one delivery becomes possible, and each compartment can be set to a specific temperature zone. The number of available compartments and their size can be fixed or adjusted flexibly. The capacity of each compartment is not necessarily equal, enabling more flexibility in the product assignment to minimize the unused capacity on each vehicle.

The multi-compartment vehicle routing problem (MCVRP) has been defined as an extension of capacitated vehicle routing problem (CVRP). Transportation network design and routing issues involving multi-compartment vehicles are frequently solved to obtain a feasible tour that serves multiple customers stops in a single trip. Various techniques such as branch and cut algorithm combined with bin packing problem have been applied to solve the multi-compartment vehicle loading problem [8].

1.3. Thailand fresh fruit exports

Thailand has become one of the world's largest fruit exporters because of product quality [9]. However, the main challenge is how to maintain a high-quality standard of fruits while minimizing the total operating cost. Therefore, careful transportation planning can be a critical element to success for Thai exporters.

China is one of the main destinations of Thai fruit exporters. The Chinese market has emerged as a popular destination for Southeast Asian fruit export markets regarding the China-ASEAN free trade zone. Road and sea freight are popular modes of transporting fresh fruits from Thailand to China. The products are exported by crossing ASEAN borders or shipping from port to port with varying distances, circumstances, and customs clearance processes. Even though sea routes usually are less expensive than land routes, the ideal route from Thailand to China is heavily influenced by other factors such as stakeholders' circumstances and types of fruit. In addition, a continuous improvement in transportation infrastructure increases route links between Thailand and China, making transportation via trucks more efficient.

The tropical Thai fruits have various harvesting seasons and various transport temperature requirements. For example, the highly popular fruits, Durian, Mangosteen, and Longan, all have different harvesting seasons. According to the Thai Office of Agricultural Economics exporting statistics(Fig. 1), Durian and Mangosteen usually ship in May, whereas Logan has the highest at the fourth quarter of the year. From July through September, the export volume of three types of fruit was distributed evenly. Due to varied shipping amounts and temperature requirements, utilizing multi-compartment vehicles could be beneficial for consolidating different fruit types throughout the offseason within the same vehicle.

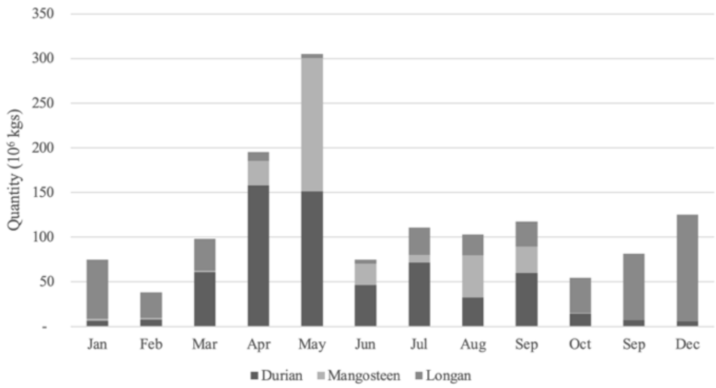

Fig. 1: Export quantity (kgs) of Durian, Mangosteen, and Longan in 2020

Accordingly, this study examines and analyses the optimal route for transporting Thai fresh fruits to China. With a significant increase in export growth rate and an expansion of connecting routes from

Thailand to China, an appropriate distribution network design is critical for market competitiveness and profitability.

The remainder of the article is organized as follows. Section 2 presents related work. Then, the problem description is described in section 3. Section 4 discusses the mathematical model formulation. Next, section 5 presents computational experiment results. Lastly, section 6 conclusions and discusses the future work directions.

2. Related Work

Various models and policies about exporting perishables commodities from Thailand are studied. For example, the time-cost model and qualitative decisions had been employed to examine six alternative international routes from Thailand to China, collecting data from surveys and in-depth interviews and all information-related routes from port/border to port/border [9]. As a result, the optimal route is determined by stakeholders' decision criteria and conditions. In general, sea routes are much less expensive than road transportation. However, in addition to the shipping time, numerous other issues must be considered, such as long customs processes and the possibility of product quality degradation.

Furthermore, the beverage transportation model from Thailand to Cambodia that aims to minimize cost, time, and risk has been studied [10]. The time-cost model was applied to determine the duration and expense of each route. In addition, the qualitative technique is utilized for risk assessment by interviewing specialists or logistic service providers. The in-depth systemic analysis and prioritization of decision criteria have been conducted by identifying risk variables and giving a weight scale. A zero-one goal programming strategy is applied to solve the optimal path selection problem. As a result, the optimal route is decided for multi-modal transportation based on cost, time, and risk.

In addition, various research has developed a mathematical model as well as algorithms to solve logistic problems in an agricultural setting. For example, a multi-objective model has been developed for the Thai sugar industry [11, 12]. The model utilizes multi-objective mixed integer programming to optimize stakeholders' objectives (e.g., economic objectives and environmental impact). In addition, Particle Swarm Optimization (PSO) is applied for finding an optimal solution. Results show that maximizing sugar production volume may not optimize the entire sugar supply chain objectives. On the other hand, scarifying some sugar production volume may improve the profitability for all stakeholders.

3. Problem Description

The problem in this study is a multi-criteria route selection with a multi-compartment loading problem. Due to varied harvesting periods, Thai exporters may have to either consolidate the shipment with different temperatures or split delivery into several vehicles during the low season. In addition, each shipment should be delivered within a specific total transportation time to prevent the spoilage of fruits at the destination. Note that, because of fruit characteristics, the maximum allowable transportation time throughout the logistics, which reduces the problem of fruits ripening before arrival, could be estimated. To solve the mentioned problem, this article proposed a mathematical model that combines the shortest path problem and multi-criteria route selection problem to create the optimal distribution route for a truck. The objective is to minimize the total transportation costs while retaining the quality of the products. In addition, the method also aims to minimize the number of vehicles used by utilizing different chambers in a vehicle.

To obtain the optimal route selection in regards to the proposed mathematical model, this problem is formulated under assumptions, and all notation and elements are determined as follow:

3.1. Vehicle types and their compartment capacity

Let

- $V = \{1, 2, \dots, v\}$be a set of vehicles available for transportation. Each vehicle is identical with the same total capacity P. The partition that separates each chamber is adjustable.
- $T = \{1,2, \dots, t\}$ be a set of compartment layout utilized on each vehicle (Fig.2)
- $C = \{1, 2, \dots, |t|\}$be a set of the available compartment.

- A_{ct} be a binary parameter indicating whether compartment c exists in layout t. (e.g., $A_{21} = 0$)
- cap_{tc} denotes the capacity of compartment c in layout type t.

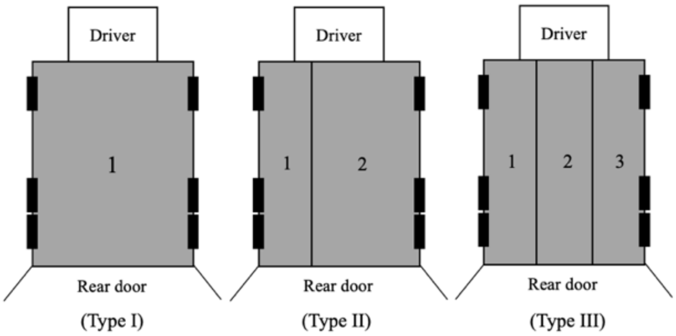

Fig. 2: Vehicle compartment layouts.

Note that, in this study, the total vehicle capacity is predefined, and type of layout is limited to three different types.

- Type I ($T = 1$): A single compartment is utilized for one product type. ($cap_{11} = P$).
- Type II ($T = 2$): Two compartments are used when shipping two different types of fresh fruit in one shipment. ($cap_{21} = P/3$ and $cap_{22} = 2P/3$).
- Type III ($T = 3$): If the container is utilized up to three compartments, the capacity of the container is split equally. ($cap_{31} = cap_{32} = cap_{33} = P/3$)

3.2. Network elements

The transportation route consists of a directed graph $G = (N, E)$ where $N = \{0, 1, 2, \ldots, n\}$ is the set of nodes. The nodes represent transit cities while $\{0\}$ is the location of the origin and $\{n\}$ represents the location of the destination. $E = \{(i, j) | i, j \in N, i \neq j\}$ is the set of edges connecting different cities. Edge (i, j) is associated with transportation time (tt_{ij}), handling time (ht_j), transportation cost (tc_{ij}), and handling cost (hc_j). FIX_v is denoted as a fixed cost of operating vehicle v.

3.3. Fresh fruit and shelf life

Let $F = \{1,2, \ldots, f\}$ be a set of fresh fruit types, and W_f are denoted as the total weight of fresh fruits required to be shipped on a given day. Different types of fruit cannot be mixed in the same compartment due to their specific requirement but can be assigned to any compartment for transportation. Each fresh fruit is assumed to be transported at optimal temperature points in each compartment, and the overall shipment quality starts to decay as the distribution begins. Q_{v_0} is denoted as the initial quality of products on vehicle v at the origin $\{0\}$. The initial quality at optimal temperature is assumed to be 100%. Q_{v_n} is denoted as the quality of products on vehicle v at the intermediate destination $\{n\}$. Equation (1) is utilized to calculate the shipment's overall quality[13].

$$Q_{v_n} = Q_{v_0} e^{-\varphi T} \tag{1}$$

Where φ is fruit decay rate, and T is a total time. (Note that the decay rate of fruits transported in the refrigerated truck is approximately 0.0012 hour^{-1} [13].)

In addition, Equation (1) can be used to derive the maximum time allowable of vehicle v, which denotes as B_v. In addition, the acceptable quality loss percentage for fresh fruit is between 8% and 23% of initial quality [13]. Table 1 presents the maximum available time regards the quality at the destination.

SL_{vf} denotes shelf life of fruit f if kept at an optimal temperature at vehicle v, and the least shelf lift of any fruit in vehicle v $\left(\min_{v}\{SL_{vf}\}\right)$ denotes as m_v. The maximum time allowable is preselected and cannot exceed the minimum shelf life of fruit.

3.4. Decision variables

- a_{vt} is a binary variable: 1 if vehicle v with layout type t is available; 0 otherwise.

- x_{vtcf} is a binary variable: 1 if fresh fruit f is assigned to compartment c on vehicle v with layout type$t$; 0 otherwise.
- $y_{vtcf}$is a loads quantity (in kgs) of fresh fruit f to compartment c on vehicle v with layout type$t$.
- $z_{vij}$is a binary variable: 1 if vehicle v travels from city i to city$j$.

Table 1: Effect of transportation time to products quality

Quality (%)	Maximum total time(hours)
92	69.5
90	87.8
88	106.5
86	125.7
84	145.3
82	165.4
80	186.0
78	207.1

4. Mathematical Model Formulation

The mathematical model for selecting an optimal route from Thailand to China associated with vehicle layout selection and fresh fruits assignment can be formulated as follows:

4.1. Objective

$$\min \sum_i \sum_j ((tc_{ij} + hc_j)\, z_{vij}) + \sum_v \sum_t FIX_v\, a_{vt} \tag{2}$$

4.2. Constraints

$$\sum_t a_{vt} \leq 1;\ \forall v \in V \tag{3}$$

$$\sum_f x_{vtcf} \leq A_{tc} a_{vt};\ \ \forall v \in V, t \in T, c \in C \tag{4}$$

$$y_{vtcf} \leq cap_{tc} x_{vtcf}; \forall v \in V, t \in T, c \in C, f \in F \tag{5}$$

$$\sum_v \sum_t \sum_c y_{vtcf} = W_f;\ \forall f \in F \tag{6}$$

$$\sum_j^n z_{v0j} \leq a_{vt};\ \forall v \in V, t \in T \tag{7}$$

$$\sum_i^n z_{vik} = \sum_j^n z_{vkj}\ ;\ \forall v \in V, k \in N \setminus \{0\} \tag{8}$$

$$\sum_i^n z_{vin} \leq 1;\ \forall v \in V \tag{9}$$

$$\sum_i \sum_j ((tt_{ij} + ht_j) z_{vij}) \leq B_v; \forall v \in V \tag{10}$$

$$B_v \leq m_v;\ \forall v \in V \tag{11}$$

$$y_{vtcf} \geq 0;\ \forall v \in V, t \in T, c \in C, f \in F \tag{12}$$

$$a_{vt} \in \{0{,}1\}; \forall v \in V, t \in T \tag{13}$$

$$y_{vtcf} \in \{0{,}1\}; \forall v \in V, t \in T, c \in C, f \in F \tag{14}$$

$$z_{vij} \in \{0{,}1\}; \forall v \in V, i, j \in N \tag{15}$$

The objective function minimizes the total cost of all vehicles used, consisting of total transportation (variable costs) and fixed costs. Constraint (3) represents vehicle layout selection constraint, ensuring that only one type of compartment layout can be selected on each vehicle. Constraint (4) - (6) represent fruit assignment constraint. Constraint (4) ensures that a compartment of any layouts could be used only for one fresh fruit type. Constraints (5) and (6) ensure that the assigned amount must not exceed the selected compartment capacity and meet the total quantity requirement. Constraint (7) - (11) represent route selection constraint. Constraint (7) provides that just one edge is chosen from origin to transit node if the vehicle v is activated. At the same time, constraint (8) specifies that the total inflow and total outflow are equal at any transit city. Constraint (9) enforces that just one edge links to a destination node. Constraints (10) and (11) ensure that the total transportation time must not exceed the allowable maximum total time; meanwhile, the maximum total time requirement must not exceed the least fresh fruit shelf life. Constraint (12) -(15) define the model's decision variables.

5. Computational Experiment

The mathematical model is applied to fresh fruit exportation data from Talaad-Thai (Thailand) to Nanning (China) as an example of a real-life case.

5.1. Instance generation

There are 18 route segments with 14 cities connecting Talaad-Thai to Nanning. The relevant data, obtained from [9], are shown in Table 2 and 3. In addition, Durian, Logan, and Mangosteen are chosen as instances for this problem. Optimal temperature and shelf-life data are presented in Table 4 [14]. The quantity requirement is randomly generated based on the harvesting period, ranging from 10,000 kgs to 100,000 kgs. All vehicles have identical attributes and the same maximum capacity of 30,000 kgs.

Table 2: The available cities and segments

Segment	From	To	Modes
1	Talaad Thai	Beungkan	Road
2	Talaad Thai	Mukdahan	Road
3	Talaad Thai	Nakhonpathom	Road
4	Talaad Thai	Laemchabang Port	Road
5	Beungkan	Paksan	Road
6	Mukdahan	Suvannakhet	Road
7	Nakhonpathom	Khommuan	Road
8	Laemchabang Port	Haiphong Port	Sea
9	Laemchabang Port	Qinzhou Port	Sea
10	Laemchabang Port	Guangzhou Port	Sea
11	Laemchabang Port	Fangchenggang Port	Sea
11	Paksan	Hanoi	Road
12	Suvannakhet	Hanoi	Road
13	Khommuan	Hanoi	Road
14	Haiphong Port	Hanoi	Sea
15	Hanoi	Nanning	Road
16	Qinzhou Port	Nanning	Road
17	Guangzhou Port	Nanning	Road
18	Fangchenggang Port	Nanning	Road

Table 3: Associated cost and time

Segment	Cost ($)		Time (hours)	
	Transportation	Handling	Transportation	Handling
1	700	0	12	0
2	800	0	10	0
3	1,300	0	11	0
4	290	0	2.5	0
5	540	220	6	4
6	580	220	5	2.5
7	350	220	3.5	3.5
8	1,300	120	90	24
9	1,495	120	144	24
10	1,700	120	168	24
11	1,210	120	144	24
11	1,510	760	13	4
12	2,070	750	18	3
13	1,430	820	12.5	4
14	720	210	8	24
15	520	1,400	3	2.5
16	380	110	2.5	15
17	1,500	210	8.5	24
18	375	210	4	27

Table 4: Optimal temperature and shelf-life for the selected fruits

Fruit	Optimal Temperature	Shelf-life
Durian	14 ± 1 °C	3-5 weeks
Longan	5 ± 1 °C	2-4 weeks
Mangosteen	13 ± 1 °C	2-4 weeks

5.2. Result and discussion

The data sets are pre-processed and solved by CPLEX. Due to the generated data instances, three alternative optimal routes are obtained from adjusting acceptable quality at the destination, ranging from 94 percent to 78 percent (Table 5). By decrementing the desired quality by 2%, the optimal route remains unchanged until the desired quality reaches 84 percent. When the quality is set to less than 84 percent, the cost has reduced. The lowest total cost is discovered when the quality is set at 78 percent, which does not exceed the acceptable quality loss. Hence, the quality setting has a direct impact on route selection.

Lastly, compared to the single compartment vehicle, the experimental results indicate that the use of the multi-compartment vehicles minimizes the number of vehicles used each day, resulting in a 22.90% reduction of a total cost, on average.

Table 5: Optimal path for each fruit quality

Route	Selected segments	Quality(%)	Total time(hours)	Total cost($)	Reduction(%)
1	1, 5, 11, 15	94.80	44.50	17,325	25.00
2	4, 8, 14, 15	83.13	154.00	14,055	22.94
3	4, 11, 18	78.52	201.50	6,990	20.75

6. Conclusion

In transporting fresh fruits, a refrigerated vehicle with a multi-compartment has been widely used because of the ability to consolidate different fruits to different compartments and the ability to separately control the temperature for each compartment to prolong the quality of the fruits. The challenge is how to create an optimal route for the trucks that can balance between transportation cost and quality of the fresh fruits. The reason is that a route with a longer transportation time may cost less, but the quality of products at the destination is also reduced.

Therefore, in this research, a mathematical model combining the shortest path problem for multi-compartment vehicles to deliver fresh fruits is developed. The model aims to minimize total transportation costs while maintaining the quality of the product at the desired level.

The Thai fruit exportation data is selected as an instance to validate the model. Results indicate that the model delivers an optimal path for the vehicles regarding the total transportation cost and the destination's desired fruit quality. In addition, the results also indicate that the different levels of the fruit quality at the destination also influence the route selection of vehicles. In addition, a multi-compartment vehicle can reduce total transportation cost compared to a single-compartment vehicle.

Researchers are recommended to address the following future research directions. 1) Research on the situation where different layouts of vehicles cost differently. 2) Study the case where vehicles have various capacities. 3) Examine the case that different fruits have different decay rates or decay functions.

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