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Modelling and Simulation of the Single-Period Vehicle Routing Problem in the Agriculture Industry

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ABSTRACT

This paper aims to discuss the concept of modeling and simulation for addressing transportation challenges in Malaysia's agriculture industry, focusing on the capabilities of distribution centers (DC) and collection centers (CC). To identify the optimal solution for the single-period vehicle routing problem (SP-VRP), we developed an optimization model that accurately represents the real-world problem, accompanied by a transportation problem simulation. The challenge involves determining the collection quantities, times, and routes to the CCs within the SP-VRP system. Consequently, we constructed a linear mixed-integer program to solve the SP-VRP. A comprehensive analysis of a sample problem demonstrates how our proposed approach is integrated. The results indicate that vehicle capacity is optimized efficiently, with an average capacity utilization of 100% across all tours and solving optimal routes allows for an evaluation of how well the model achieves this objective, as well as how different routes affect logistics performance.

1. INTRODUCTION

The agricultural industry, a key driver of global food supply, faces increasing pressure to enhance efficiency while reducing environmental impacts. The growing global population and the need for an adequate supply of safe, high-quality agri-food products are putting pressure on the agriculture sector today. In addition, there has been a global increase in the reliance on imported food of almost 50% between 2006 and 2020 [1], and the existing food supply chain has become more globalized [2].

The flow and diversity of goods have expanded in the last few decades. Goods transportation and trade have expanded more quickly than countries' GDPs [3]. Due to the growth in international trade in food from far-off sources, food shipments have travelled longer and carried more weight globally in recent decades [4]. For instance, food travelled 50% further in the UK and 25% further in the USA at the start of the twenty-first century than it did in the 1980s [5].

One of the most critical challenges lies in optimizing logistics, particularly in the routing of vehicles for transporting goods. This issue, commonly known as the Vehicle Routing Problem (VRP), is especially significant in agriculture, where the perishability of goods, dispersed production areas, and variable road conditions in rural settings pose unique constraints. Transportation costs represent a substantial portion of total expenses in agricultural supply chains. According to a report by the Food and Agriculture Organization (FAO), transportation costs in agricultural supply chains can account for as much as 40-60% of total distribution expenses. This is particularly true in regions where agricultural production occurs in remote areas, far from consumer markets or processing centers. For instance, in Latin America, rural transport costs can increase significantly due to poor infrastructure, exacerbating supply chain inefficiencies and raising the cost of food for consumers [6]. Optimizing vehicle routing could therefore lead to substantial cost savings for producers and logistics companies, while making agricultural products more affordable for consumers.

The environment is impacted by the rise in the amount and distance that food and food animals' travel. About 25% of greenhouse gas (GHG) emissions associated with global energy consumption are produced by the transportation sector, and 75% of these emissions are related to road transportation [7]. According to projections made by the study [8], the CO_2 emissions from all vehicle categories in Sweden are expected to rise from 18.5 million tons in 1998 to 25 million tons in 2020, suggesting that the freight transport industry may play a larger role in global warming. Reducing emissions from the transportation sector, especially transportation within the agriculture sector, should receive more emphasis in the endeavours to lessen the danger of climate change [9].

In addition to cost considerations, the environmental impact of transportation in agriculture is an increasingly critical concern. According to the International Energy Agency (IEA), the transport sector accounts for approximately 24% of global CO_2 emissions, and agricultural logistics are a significant contributor within this sector due to the high fuel consumption of heavy vehicles transporting goods over long distances [10].

Research has demonstrated that optimizing vehicle routes can reduce fuel consumption by up to 10-20%**,** depending on the efficiency of the routing algorithms and the specific logistics network being optimized [11]. In the European agricultural sector, for example, simulation models have shown that a reduction in fuel consumption from optimized routing can lead to a 15% decrease in greenhouse gas emissions without compromising delivery times [12].

In general, there has been an increasing amount of focus on the food supply chains. The primary causes of this are the following: consumers' decreased interest in chemical-based food production; growing societal awareness of sustainable food production, processing, and transportation; and the growing impact of food transportation on the environment, logistics costs, and animal welfare. In an endeavour to tackle these problems, the local food supply chain is making a comeback as a substitute food supply network. Despite the growing demand for locally grown food, the main logistical obstacles facing local food systems necessitate a thorough analysis to pinpoint the main bottlenecks and devise solutions. For the local food supply chain, this calls for the creation of effective and efficient logistical systems. Research projects aimed at enhancing the local food systems' logistical performance are still uncommon. Nonetheless, the idea of local food logistics may gain traction, and this paper can make a significant contribution to it by enhancing the logistical capabilities of regional food distributors and producers.

Furthermore, route optimization is one of the most extensively studied areas within transportation research, focusing on creating the most cost-effective and efficient distribution patterns to serve dispersed clients [13]. This approach has been applied in various fields, including forest harvesting, solid waste collection, and agricultural goods transport, to reduce operational costs and emissions. The primary goals of route optimization are to minimize travel distances and reduce the fleet size of vehicles used [14]. Therefore, route optimization analysis is crucial for enhancing goods distribution systems in the agriculture industry. An integrated strategy for supply chain management and logistics should be created to lessen the limitations and enhance the commodities distribution system [15, 16].

Figure 1 illustrates the basic concept of the goods distribution system in Malaysia's agriculture industry. It connects farmers, collection centers (CC), distribution centers (DC), and retailers into a cohesive supply chain system. This system requires efficient coordination of logistics activities through an integrated approach, where the distribution of agricultural products is managed from the farmers, through the CCs and DCs, and finally reaches the retailers as the final stage.

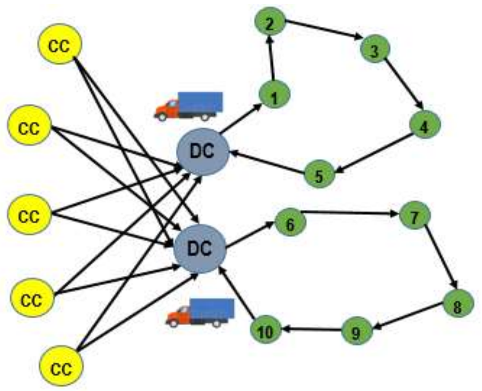

Figure 1. Goods distribution system in the agriculture sector

Therefore, the focus of this paper is to improve the goods distribution system which is the collection and transportation of agricultural products. This comprises product assessment from each CC to the DC and determining the best routes with regard to travel distance and time as well as trips. We developed a linear programming model and applied appropriate constraint optimization techniques. To solve the mathematical problems and analyze the results, we used A Mathematical Programming Language (AMPL). Figure 2 shows the simulation of the location for each DC and CC scattered around Kedah Darul Aman, Malaysia. The triangle symbol on the Map of Kedah stands as DC and the circle symbol stands as DC.

Figure 2. Map of Kedah, locations of the DC and CC

Given the economic and environmental stakes, the importance of addressing the VRP in the agriculture industry cannot be overstated. By implementing advanced modeling and simulation techniques to optimize vehicle routes, agricultural supply chains can not only reduce costs but also contribute to global efforts to mitigate climate change. The need for such optimizations is especially urgent in the context of growing global demand for sustainable agricultural practices and climate-resilient supply chains.

2. LITERATURE REVIEW

The raising and breeding of plants, animals, and fungi for the production of food, fibre, biofuels, medicinal plants, and other goods that support and enhance human life is known as agriculture. Food, fibre, fuel, and raw materials are the four basic categories into which agricultural products come. Agriculture employs nearly one-third of all workers worldwide, second only to the service sector, albeit during the past few centuries, the share of agricultural workers in developed countries has drastically decreased [17, 18]. There just wouldn't be enough food without agricultural systems' increased production of edible biomass. Nonetheless, massive amounts of land, water, and energy resources are required to support this level of food production. Thus, the primary method by which humans affect terrestrial ecosystems is through agriculture [19]. The world's food needs, the cost and availability of resources required to sustain high levels of productivity, and the more effective technology improvement of agriculture will all have an impact on how agriculture is impacted in the future.

Improving Supply Chain Management's (SCM) efficacy and efficiency is one of the primary industrial initiatives. Thus, agencies or authorities, concentrating on the upper echelons of supply chain management, employ both distribution centres and collection centres to gather crops before their distribution to market segments that are being divided. The location with the highest concentration of CC is where the crops are harvested, which is typically close to the surrounding farms and settlements. Before being transferred to the DC, all of the crops are graded, tagged, and gathered here. The DC will serve as the centre for receiving products and adding value, after which it will distribute agricultural products to the network of supermarkets and institutions.

To carry out the plan, the crops must be delivered between the CC and DC. Managing operating expenses is a primary priority of the supply chain's highest echelons. Transportation expenses comprise the operating costs, which are contingent upon the amount of money and time expended. Therefore, agencies must strike the right balance between optimizing their resources and expertise and minimizing the costs associated with crop distribution. A proper balance will guarantee peak performance, fulfilling their supply chain requirements. The cost of transportation was determined by the trip's distance. Agencies should also employ the appropriate amount of transport and carrier to maximize resources and have the proper scheduling flow for transportation to reduce the overall cost of their operations.

2.1 Definition of supply chain in agricultural

Producers from developing countries must have access to local, regional, and international markets through agrifood chains and networks. The ability of agro-industrial enterprises, both large and small, to compete is impacted by changes in agri-food systems. To remain competitive, they must both innovate and cut costs while improving customer service. Supply Chain Management (SCM) can be useful in this situation. To create and deliver goods as effectively and efficiently as possible to meet customer or market demands, supply chain management (SCM) plays a crucial role in integrated planning, implementation, coordinating, and regulating all business operations and activities [20].

SCM are crucial to modern business studies. A supply chain is a network made up of material suppliers, manufacturing sites, distribution centres, and clients that are linked by the forward movement of materials, the return flow of information, and the flow of financial resources. SCM is often important in the industrial sector, but it is also playing an increasingly significant role in the food and fresh produce industry. Linkages in the supply chain from the main producer to the customer's door are the focus of supply chain management. In order to achieve better service levels and significant cost reductions, it aims to remove obstacles between each unit.

2.2 Agriculture marketing system and supply chain management in Malaysia

As noted in the study [21], the traditional agricultural marketing system and the modern supply chain system differ significantly in how they handle various marketing functions, such as production, procurement, pricing, buying and selling, product development, processing, logistics, ICT applications, and market information. For instance, the new supply chain focuses more on process efficiency, while traditional marketing tends to emphasize economic aspects. In the new system, retailers play a more central role compared to wholesalers in the traditional system. Additionally, the production marketing network in the new supply chain is more integrated and value-chain oriented, with marketing channels lacking distinct functional roles. Technology drives both production and processes in the new system, allowing for customized products and private labeling.

When agriculture is considered more holistically in the agribusiness area, supply chain management will create value at every stage of the chain. This will provide the framework for agriculture to propel global development by using national advantages and potential in input, processing, wholesale and retail commerce, and international trade. Therefore, agriculture will support Malaysia's agro-based companies' economic growth through their connection to the supply chain network.

2.3 Distribution centre (DC) and collection centre (CC)

A collection centre (CC) is a place where the agricultural crops from the farmers are collected at one small place before being distributed into different distribution centres (DC) for final transportation towards the market. Many advantages and benefits will result from an optimal CC because it connects food producers, distributors, and consumers/retailers. This will allow for the coordinated distribution of locally produced food and make it easier to integrate food distribution from small-scale local supply systems into large-scale channels for food distribution at every stage of the supply chain integration process [22].

DC is a place where the product crop from CC is sent before it is sent to the market. A DC is a crucial element in a supply network, as it provides essential functions that facilitate the flow of materials up the supply chain [23]. Higginson and Bookbinder further elaborate that a DC stores fresh goods, such as vegetables and fruits, either temporarily or for extended periods. Additionally, it handles activities such as processing products, breaking down vehicle loads, and assembling shipments. DC is equipped with facilities for repackaging, storage, fermentation and logistics delivery service.

2.4 Wholesalers

Wholesalers are the parties to which they act as traders who purchase a product or merchandise at a large quantity level at any one time and deliver it to small customers or buyers who may also be categorized as intermediaries in a business. Typically, they assist the producer in delivering physical and storage shipments to wholesale buyers and retailers in the trading and suppliers' chain. According to the study [24], a wholesale agricultural market can set prices for items since it always has a stable supply without price tags. In view of this, wholesalers have a crucial role in the agricultural supply chain.

Normally, the wholesaler can help with business integration planning through promotional assistance and price determination. Wholesalers also can act as an extension of the producer workforce in business. That's why they have always had a good relationship with the producer to improve business sustainability. Wholesalers need to keep producers up to date based on market conditions nowadays. They also need to be aware of market environment changes in order to avoid problems in business activity. Their vital role in supply chain management is important for producers especially those who need them to strategize market development.

3. MODELLING THE SP-VIRP

In agricultural supply chains, many products, particularly perishable goods such as fruits, vegetables, and dairy, have short shelf lives. This requires deliveries to be made within narrow time windows to prevent spoilage. As a result, the logistics involved often focus on short-term, day-to-day operational decisions, where each delivery period is relatively independent of the next. By modeling the problem as a single-period vehicle routing problem (SP-VRP), we can simulate these daily logistics more realistically, allowing for fine-tuned, efficient routing solutions that address the immediate needs of the supply chain.

A single-period horizon also simplifies the complexity of the problem, enabling a more detailed exploration of routing strategies within one time period. This allows us to focus on specific factors such as vehicle capacity, route optimization, and fuel consumption without the added complexity of considering multiple periods. Given that each day's routing problem in agriculture can vary due to changes in demand, weather, or vehicle availability, a single-period approach is well-suited to capture these variations effectively.

The SP-VRP as described in this paper, involves a single distribution center (DC) utilizing a fleet of uniform vehicles to gather agricultural products from several geographically spread collection centers (CC) within a specified planning horizon. It is assumed that the demand rates at the collection centers are known and constant, and travel times remain unchanged over time. The assumptions of known and constant demand rates and unchanging travel times are made primarily for the sake of model simplification and to focus on the key challenges of vehicle routing in agriculture. These assumptions allow for a more tractable model and are reasonable for a SP-VRP, particularly in rural or developing regions where traffic patterns are more predictable and demand at collection centers is relatively stable. While these assumptions may limit the model's applicability to highly dynamic or unpredictable environments, they provide a solid foundation for optimizing agricultural logistics.

The goal of this SP-VRP is to optimize the quantities collected from each CC, determine the delivery schedules, and plan the vehicle routes in order to minimize the overall distribution costs. To formulate our model for the SP-VRP, the following assumptions are made:

- The model excludes the amount of time needed to load and unload the vehicle.
- It is considered that the cost of transportation is related to the distance travelled.
- Split deliveries are prohibited; only one vehicle is permitted to fully replace each CC.

The following subsections detail the pertinent variables, parameters, and a linear mixed-integer formulation of the SP-VRP:

Let $H = \{1, 2, \dots T\}$ represent the set of consecutive periods in the planning horizon, indexed by t, and $H^+ = H \cup \{0\}$. Let τ_t denote the duration of period t in time units, such as 8 working hours. Define S as the set of CC, indexed by i and j, with $S^+ = S \cup \{r\}$, which represents the DC. A fleet of vehicles V is employed to service these CCs. The remaining relevant parameters of the model are provided below:

- φ_{jt}: the fixed handling cost (in \$) per delivery at location $j \in S^+$ (CC and DC) in period $t \in H$;
- η_{jt}: the per unit per period holding cost of the product at location $j \in S^+$ (in \$ per tons per period);
- ψ^v: the fixed operating cost of vehicle $v \in V$ (in \$ per vehicle);
- δ_v: travel cost of vehicle $v \in V$ (in \$ per km);
- κ^v: the capacity of vehicle $v \in V$ (in tons);
- v_v: average speed of vehicle $v \in V$ (in km per hour);
- θ_{ij}: duration of a trip from CC $i \in S^+$ to CC $j \in S^+$ (in hour);
- d_{jt}: the stationary demand rate at CC j (in tons per hour) in period $t \in H$.

The model variables are defined as follows:

- Q^v_{ijt}: The quantity (in tons) of product remaining in vehicle $v \in V$ when it travels directly to location $j \in S^+$ in $i \in S^+$ from location $i \in S^+$ during period $t \in H$. This quantity is zero if the trip (i,j) is not part of any route taken by vehicle $v \in V$ in period t;
- q_{jt}: The quantity (in tons) collected at location $j \in S$ in period $t \in H$, otherwise, it is zero;
- x^v_{ijt}: A binary variable set to 1 if location $j \in S^+$ is visited immediately after location $i \in S^+$ by vehicle $v \in V$ in period $t \in H$; otherwise, it is zero.
- y^v_t: A binary variable set to 1 if vehicle $v \in V$ is in use during period t; otherwise, it is zero.

SP-VRP: Minimize

$$CV = \sum_{t \in H} \sum_{v \in V} \left[\psi^v y^v_t + \sum_{i \in S^+} \sum_{j \in S^+} (\delta_v v_v \theta_{ij} + \phi_{jt}) x^v_{ijt} \right] \quad (1)$$

Subject to:

$$\sum_{v \in V} \sum_{i \in S^+} x^v_{ijt} \le 1, \forall j \in S, t \in H \quad (2)$$

$$\sum_{i \in S^+} x^v_{ijt} - \sum_{k \in S^+} x^v_{jkt} = 0, \forall j \in S^+, t \in H, v \in V \quad (3)$$

$$\sum_{i \in S^+} \sum_{j \in S^+} \theta_{ij} x^v_{ijt} \le \tau_t, t \in H, v \in V \quad (4)$$

$$\sum_{v \in V} \sum_{i \in S^+} Q^v_{ijt} - \sum_{v \in V} \sum_{k \in S^+} Q^v_{jkt} = q_{jt}, \forall j \in S, t \in H \quad (5)$$

$$Q^v_{ijt} \le k x^v_{ijt}, \forall j \in S^+, t \in H, v \in V \quad (6)$$

$$q_{jt} \ge d_{jt} \tau_t, \forall j \in S, t \in H \quad (7)$$

$$x^v_{rjt} \le y^v_t, \forall j \in S^+, t \in H, v \in V \quad (8)$$

$$x^v_{rjt}, y^v_t \in \{0,1\}, Q^v_{ijt} \ge 0, q_{jt} \ge 0, \forall j \in S^+, t \in H, v \in V$$

Three cost components make up the objective function (1): the total fixed operational cost of employing the vehicle(s), the total cost of transportation, and the total cost of delivery handling after each period. Constraints (2) guarantee that every CC is visited no more than once during time t. A vehicle must depart from a CC after serving it to the DC or the next CC, according to Constraints (3). Constraints (4) make sure that vehicles finish their routes in a single travel period, therefore a vehicle's total travel duration shouldn't be longer than the number of scheduled working hours for each period. The amount collected to a CC is determined by Constraints (5), which also exclude sub-tours. The vehicle capacity constraints are given by (6) and ensure that the variables Q^{v}_{ijt}, cannot carry any cumulated flow unless x^{v}_{ijt} equals 1. Constraints (7) is demand at the CC does not exceed the quantity collected from the CC. Constraints (8) indicate that a vehicle cannot be used to serve any CC unless it is selected.

4. ANALYSIS OF THE SP-VIRP

The agriculture sector in Malaysia is overseen by the Ministry of Agriculture and Food Security (MAFS). The Federal Agricultural Marketing Authority (FAMA) is one of the key agencies directly involved in farming and marketing. FAMA plays a crucial role at the second level of the supply chain, acting as a direct buyer from both independent and contract farmers [25]. For independent farmers, FAMA collects the produce from the farm upon request, whereas contract farmers follow a set harvesting schedule provided as a guideline. Despite acting as a government corporation, FAMA is able to provide at a competitive price since they have built several marketing channels. FAMA handles all transportation arrangements, which are run out of their operation centre [26].

At the output stage of agricultural production, FAMA established a collection centre (CC). Through improved quality grading, post-harvest handling procedures, and labelling as a route for agricultural information, this research seeks to address issues with agriculture marketing. In addition, FAMA established distribution centres (DC) in significant urban centres close to the wholesale market complex. DC serves as the centre for receiving products and adding value, after which it distributes agricultural products to supermarkets and network institutions. Facilities for repackaging, storage, fermentation, and logistical delivery services are available at distribution centres.

To demonstrate the behavior of our proposed model, we present an example case of the single-period vehicle routing problem (SP-VRP). The parameters used in the numerical example were chosen based on a combination of real-world data and reasonable assumptions**.** Future research could further refine these parameters by collecting more precise, region-specific data. In this scenario, we consider 20 collection centers distributed around the distribution center, as shown in Figure 3. These CCs, whose demand rates are thought to be steady, are dispersed across the DC at the coordinates (x, y). Assumed to be ready for collection from the DC is a fleet of vehicles.

A fleet of uniform vehicles V, each with a capacity κv of 60 tons, is available to collect the products. The fixed operating cost $\psi\ v$ for each truck is \$50. The cost of travel is \$1 per kilometer, with trucks moving at an average speed of 50 km/h. For each collection center (CC), the inventory holding costs ηj are generated randomly and uniformly within the range of 0.1 to 0.5 in USD per ton per hour. The time unit τt is assumed to be 8 hours, and the fixed delivery handling cost φj is uniform across all collection centers. Table 1 presents the values of these parameters for the SP-VRP.

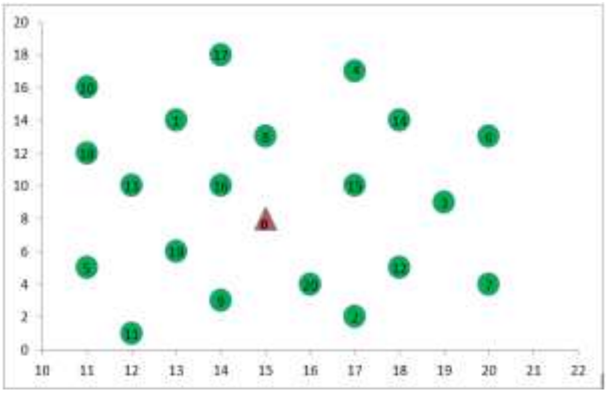

Figure 3. Illustrating locations of the distribution centre (DC) and collection centre (CC)

Table 1. Parameters for each of the 20 collection centres for the SP-VRP

Collection Centre (CC)	CoordinateX	CoordinateY	Demand (ton/hr)	Fixed Handling Cost
CC1	15	08	2.23	25
CC2	13	14	2.54	25
CC3	17	02	2.99	25
CC4	19	09	1.58	25
CC5	17	17	1.31	25
CC6	11	05	2.60	25
CC7	20	13	1.35	25
CC8	20	04	2.71	25
CC9	15	13	1.97	25
CC10	14	03	1.95	25
CC11	11	16	2.09	25
CC12	12	01	2.05	25
CC13	18	05	2.94	25
CC14	12	10	1.88	25
CC15	18	14	1.50	25
CC16	17	10	2.55	25
CC17	14	10	2.09	25
CC18	14	18	1.79	25
CC19	11	12	1.28	25
CC20	13	06	2.84	25

The 20-CC instance of the SP-VRP was solved using AMPL with CPLEX 12.6.3. The optimal solution for the twenty collection centers in the SP-VRP is illustrated in Table 2. In this solution, a single homogeneous truck is used to collect agricultural products from the collection centers. As illustrated in Table 2, the CCs are assigned to six routes, in which the vehicle 1 makes the tour V_1=(0-8-1-18-0), tour V_2=(0-10-17-4-14-0), tour V_3=(0-12-9-11-5-0), tour V_4=(0-15-6-3-0), tour V_5=(0-19-13-16-0) and tour V_6=(0-20-2-7-0).

Table 2. Optimization of transportation model between DC and CC

Route	DC to CC
Route V_1	0-8-1-18-0
Route V_2	0-10-17-4-14-0
Route V_3	0-12-9-11-5-0
Route V_4	0-15-6-3-0
Route V_5	0-19-13-16-0
Route V_6	0-20-2-7-0

For instance, in route $V1$ (0-8-1-18-0), a homogeneous vehicle collects 21.68 tons of product from CC8, 24.0 tons from CC1, and 14.32 tons from CC18, totaling a demand of 60 tons. This demonstrates efficient optimization of the vehicle's loading capacity. Similarly, for route $V2$ (0-10-17-4-14-0), the vehicle collects 15.60 tons from CC10, 16.72 tons from CC17, 12.64 tons from CC4, and 15.04 tons from CC14, also with a total demand of 60 tons. This further illustrates the effective optimization of truck loading capacity, achieving an average capacity utilization of 100% across all tours. The summary of these distribution patterns is provided in Table 3.

Table 3. Summary results for characteristics of the collection pattern

Route	Vehicle Load (ton)	Total Vehicle Load (ton)
Route V_1	(21.68 + 24.0 + 14.32)	60.00
Route V_2	(15.6 + 16.72 + 12.64 + 15.04)	60.00
Route V_3	(16.4 + 15.76 + 17.36 + 10.48)	60.00
Route V_4	(12.0 + 24.08 + 23.92)	60.00
Route V_5	(10.24 + 29.36 + 20.4)	60.00
Route V_6	(22.72 + 26.48 + 10.8)	60.00
		360.00

The vehicle capacity utilization is an important metric for evaluating the efficiency of a logistics system and solving the Vehicle Routing Problem (VRP) is to determine the most efficient routes for vehicles to follow while minimizing travel distance, time, or cost. Solving optimal routes allows for an evaluation of how well the model achieves this objective, as well as how different routes affect logistics performance.

While this study focuses on the agriculture industry from both a global and Malaysian perspective, the insights and solutions derived from addressing the SP-VRP are highly relevant to other developing countries facing similar logistics challenges. Many developing nations share common issues such as poor road infrastructure, fragmented smallholder farming systems, and limited access to modern logistics technologies**,** all of which significantly increase the complexity and cost of agricultural transportation. For instance, in Sub-Saharan Africa and Southeast Asia, road networks are often underdeveloped, leading to high transportation costs and inefficiencies in moving agricultural produce from rural areas to urban markets [27]. By optimizing vehicle routing and addressing transportation inefficiencies, these countries can reduce costs, improve food security, and enhance the sustainability of their agricultural sectors [28].

5. CONCLUSION

We investigated the single-period vehicle routing problem (SP-VRP), in which a single distribution center (DC) collects agricultural products from a set of collection centers (CC) that consume them at fixed demand rates, using a fleet of homogeneous vehicles over a defined finite horizon. The objective is to determine the optimal quantities to collect from the CCs, establish collection times, and design vehicle delivery routes to minimize total transportation costs. The SP-VRP was formulated as a linear mixed-integer program. Results from a medium-sized example case show that vehicle capacity is utilized efficiently, achieving an average capacity utilization of 100% across all tours.

Moving forward, the current model and solution will be adapted for numerical experiments and real-world challenges, including scenarios involving large CCs, as part of our future research strategy. Additionally, while this study provides valuable insights into the SP-VRP in agriculture, future research should explore multi-period extensions to account for longer-term decision-making and to capture the full complexity of agricultural logistics. These extensions could lead to even greater cost savings, improved fleet management, and enhanced environmental outcomes, making them an important direction for continued exploration.

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