

Dynamic sustainable multiple-depot vehicle routing problem with simultaneous pickup and delivery in the context of the physical internet

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Abstract

Purpose – This paper proposes an approach to solve the vehicle routing problem with simultaneous pickup and delivery (VRPSPD) in the context of the Physical Internet (PI) supply chain. The main objective is to minimize the total distribution costs (transportation cost and holding cost) to supply retailers from PI hubs.

Design/methodology/approach – Mixed integer programming (MIP) is proposed to solve the problem in smaller instances. A random local search (RLS) algorithm and a simulated annealing (SA) metaheuristic are proposed to solve larger instances of the problem.

Findings – The results show that SA provides the best solution in terms of total distribution cost and provides a good result regarding holding cost and transportation cost compared to other heuristic methods. Moreover, in terms of total carbon emissions, the PI concept proposed a better solution than the classical supply chain.

Research limitations/implications – The sustainability of the route construction applied to the PI is validated through carbon emissions.

Practical implications – This approach also relates to the main objectives of transportation in the PI context: reduce empty trips and share transportation resources between PI-hubs and retailers. The proposed approaches are then validated through a case study of agricultural products in Thailand.

Social implications – This approach is also relevant with the reduction of driving hours on the road because of share transportation results and shorter distance than the classical route planning.

Originality/value – This paper addresses the VRPSPD problem in the PI context, which is based on sharing transportation and storage resources while considering sustainability.

Keywords Simultaneous pickup delivery, Vehicle routing problem, Physical internet (PI), Demand forecasting, Simulated annealing, Sustainability

Paper type Research paper



1. Introduction

A new innovative paradigm known as the “Physical Internet” or PI was proposed in 2011 as a modern and sustainable solution to improve global logistics and supply chains (Montreuil *et al.*, 2013). The PI is described as an open global logistics supply chain of physical, digital and operational activities based on interconnectivity between all parties: suppliers, distributors and customers (Montreuil *et al.*, 2013). In a PI network, the goods are encapsulated in a standardized modular box, denoted as PI container, before being transported to other nodes in the PI network (Chargui *et al.*, 2019; Sallez *et al.*, 2016). The idea of encapsulation in PI containers is similar to pallets or container boxes in the classical supply chain. However, PI containers are more dynamic in the supply chain network for the transportation of goods.

The PI concept is quite similar to a cyber-physical system (CPS) but there are some differences. PI focuses on the whole logistics network and interconnection between nodes. It can also support single and intermodal transportation in the same network. CPS is a smart system that integrates the workflow between physical and technological elements (Nagy *et al.*, 2018). For example, trains can communicate with each other using both an automated system and physical alert signals. The PI network can comprise numerous CPSs to ensure interconnection between all the parties including vehicles, distribution centers and customer nodes. In this article, we focus primarily on the PI concept.

Nowadays, many studies focus on the PI concept and how to implement this concept in real applications. One of the most exciting aspects is the distribution process in the PI network (Ben Mohamed *et al.*, 2017; Caballini *et al.*, 2017; Fazili, 2014; Gontara *et al.*, 2019; Venkatadri *et al.*, 2016). The challenge with PI distribution is how to create reliable and flexible connections between all the PI nodes in the network, as well as how to manage resources in all the PI hubs easily. As explained in Caballini *et al.* (2017), Venkatadri *et al.* (2016), PI hubs are fully connected with suppliers (origin nodes) and customers (destination nodes). However, if the number of PI hubs is large, it is better to group them in a cluster and dynamically determine the number of hubs based on different daily demands (Kantasa-Ard *et al.*, 2019). The clustering concept not only reduces the connection complexity between all PI nodes but also improves the construction of routes between PI nodes in the network.

Some relevant studies have proposed route construction in the PI context. For example, the research by Ben Mohamed *et al.* (2017) proposed vehicle route construction for the simultaneous pickup and delivery problem. Another study (Kantasa-ard *et al.*, 2021a) proposed mixed integer linear programming (MILP) to find the optimal solution for the routing problem. A nearest neighbor search heuristic was developed to find a near-optimal solution in some instances that cannot be solved using CPLEX. However, these methods only support the delivery process between PI hubs and retailers.

There are still some research gaps in PI distribution regarding the aforementioned research. For example, in the research by Ben Mohamed *et al.* (2017), only one truck was used to pick up and deliver goods at pre-assigned retailers under that hub or distributor. Furthermore, all the trucks were required to return to their initial hubs at the end of the day. These heavy constraints are not representative of reality. Another gap in the previous research by Kantasa-ard *et al.*, (2021a) concerns inventory control at PI hubs. This research did not focus on remaining stock levels as a holding cost at each hub. However, these costs can be hefty and must be considered. Based on these gaps, we propose an attractive contribution to address them.

The contribution proposes a mathematical model as a framework for the new distribution problem in the PI context. This study focuses on the simultaneous pickup and delivery vehicle routing problem (VRPSPD). The problem is formulated using mixed integer programming (MIP) to construct feasible routes between PI-hubs and retailers and is solved using CPLEX. In the PI context, as shown in the literature review, pickup and delivery problems have rarely been addressed, especially from an operational research point of view. This contribution will help researchers formulate the transportation route for pickup and

delivery in the PI context more easily. In addition, the chosen metaheuristics, which are random local search (RLS) and simulated annealing (SA), also provide a constructive solution in the case of numerous interconnections between all nodes in the PI network.

This paper is divided into six sections. This section provides the background and primary contributions to solve the distribution problem in the PI context. [Section 2](#) reviews the literature on the distribution process in the PI context and solving methods. [Section 3](#) details the assumptions, experimental dataset and the feasible routes constructed. [Section 4](#) details the methodology and the implementation of the proposed optimization methods (MIP and metaheuristics). [Section 5](#) compares the proposed optimization methods from both classical supply chain and PI perspectives, and presents the CO₂ emissions determined through a case study involving the distribution of agricultural products. The conclusion and some future lines of research are given in [Section 6](#).

2. Literature review

This section provides an overview of the relevant literature regarding the distribution process, the pickup and delivery problem, and some route construction solving methods in the context of the PI. In addition, a comparison of the relevant literature on classical supply chains and the PI regarding the pickup and delivery problem is presented at the end of this section.

2.1 *The pickup and delivery process in the physical internet supply chain*

Several studies have examined the distribution process in the context of the PI supply chain. Firstly, research in [Fazili \(2014\)](#) proved the performance of PI logistics by comparing conventional (door-to-door) and hybrid (combination of conventional and PI) logistics concepts based on the road network. [Venkatadri et al. \(2016\)](#) developed a dispatch model between pairs of cities based on the PI context and compared it with a traditional logistics system. [Caballini et al. \(2017\)](#) defined and modeled a road network to minimize total transport costs, exploit truck capacity and reduce empty trips from one node to another. Lastly, [Gontara et al. \(2019\)](#) constructed a hub-to-hub route for the road transport of PI containers. The border gateway protocol (PI-BGP) concept was implemented in the PI network. However, this study did not consider demand and inventory in the network. These studies primarily formulated and solved the distribution problem via MILP models based on truck capacity. The distribution problem in these papers focused on movement between source nodes and destination nodes such as hubs to hubs or suppliers to customers. They performed well with small instances and proposed some future aspects to address the research gap. For instance, the researchers in [Caballini et al. \(2017\)](#) and [Fazili \(2014\)](#) suggested developing heuristic methods for larger instances and examined the construction of PI routes in a real urban transportation network, focusing more particularly on load-size in PI containers. The pickup and delivery problem in the PI context is explained in more detail in the next section.

As mentioned previously, most of the research used exact and heuristic algorithms, which are also used in traditional distribution networks ([Battarra, 2011](#); [Mor and Speranza, 2020](#)). Moreover, several studies investigating the PI distribution network also considered the efficiency of vehicle routing and inventory management between nodes in the network. Indeed, pickup and delivery are two of the main operations in the distribution process. Some previous studies have investigated the vehicle routing problem with pickup and delivery in a traditional distribution network, particularly with multiple trips. For instance, [Felipe et al. \(2012\)](#) implemented an adapted heuristic with a variable neighborhood search (VNS) to optimize transportation routes for pickup and delivery operations. The authors in [Guemri et al. \(2016\)](#) proposed a GRASP-based heuristic to solve the transportation routing and inventory control problems for multiple products and vehicles. The research also benchmarked its performance against two other reference algorithms. Additionally,

Vilhelmsen *et al.* (2016) proposed a hybrid method combining heuristic and optimality-based methods to allocate appropriate cargoes to tanks available for loading in maritime bulk shipping. The computational times were proposed to evaluate the performance of the solutions. The previous studies have demonstrated that the efficiency of pickup and delivery operations is essential for the distribution process. Excellent operations would positively offset all relevant costs in the distribution process.

The pickup and delivery problems have been equally studied in the PI context. For example, Rougès and Montreuil (2014) demonstrated how the concept of interconnectedness in the PI could solve the limitations of current crowdsourcing. The latter is a less flexible network in which parcels are processed and managed individually from point to point. The authors also demonstrated that PI can support crowdsourcing delivery. Moreover, with standard modular containers, smaller containers can be combined and thus facilitate transportation (Sallez *et al.*, 2016). Each container is also equipped with devices (e.g. RFID technology, sensors networks) to monitor and control products during transportation. Fazili (2014) and Venkatadri *et al.* (2016) have proposed that modular containers of various sizes can be embedded in different vehicles after trans-shipment at PI hubs. In Pal and Kant (2016), a PI network concept was implemented in a fresh food distribution process. The authors proposed a mechanism for decreasing empty truck miles and the carbon footprint through infrastructure sharing: hubs, trucks and handling tools in the fresh food distribution network. Furthermore, local and long-distance distribution between hubs was determined by inter-domain delivery strategies. Two other studies (Faugère and Montreuil, 2017, 2020) proposed the concept of a hyper-connected network to pick up and deliver smart lockers in the PI network; the optimization of the smart locker design was based on uncertainty demand. This concept made the pickup and delivery processes faster and more convenient for customers. In addition, this research also implemented the sustainability concept with the determination of CO₂ emissions, for instance, to control the environmental pollution of resulting from the transportation of goods. Several studies have demonstrated the benefits of the sustainability aspect in the supply chain (Ding *et al.*, 2021; Gajanand and Narendran, 2013; Helo and Ala-Harja, 2018). Sustainability is clearly a founding element in the PI approach.

Even though some studies on the pickup and delivery problem deal with single depots, few studies have considered multiple-depot vehicle routing problem (MDVRP). For instance, Ben Mohamed *et al.* (2017) proposed the concept of simultaneous pickup and delivery in the PI context with multiple depots. Each truck served a set of demand points pre-assigned to the same hub. This research also considered some constraints such as multiple periods, multi-zone urban coverage, heterogeneous fleets and multiple trips. MILP was constructed to formulate the problem, and constructive greedy and insertion heuristics were implemented to improve the solution.

Despite the small number of studies on the MDVRP in the PI context, some interesting ideas in classical distribution networks could help us to discover a novel distribution approach. The authors in Yu *et al.* (2013), for example, proposed an improved ant colony optimization with distance-based clustering to construct the set of connected routes between customers and depots. The computational time was used as the KPI to measure the routing performance. Lam and Mittenenthal (2013) also proposed a capacitated hierarchical clustering heuristic method to improve the location-routing performance with multiple depots. In another example, the authors in Ramos *et al.* (2020) developed an MILP model to enhance the performance of the MDVRP. The heterogeneous fleet and the maximum routing time were considered as the main factors in the study. These studies demonstrate that the MDVRP concept is widely implemented in classical distribution networks.

The distribution approach in this paper not only mentions the pickup and delivery problem but also focuses on the open vehicle routing problem (OVRP). The concept of the OVRP considers that the starting node and the end node in a route may not be the same. This

means that once the goods have been transported to the last customer, a truck does not need to return to its original depot (Li *et al.*, 2007). Some studies have implemented the concept of OVRP. The authors in (Li *et al.*, 2007) proposed a record-to-record travel algorithm to solve the OVRP problem of home delivery of products with a test case (200–480 customers) and compared it with existing heuristic methods in the classical supply chain. In addition, the authors in Atefi *et al.* (2018) implemented the concept of decoupling points for each route to increase the transportation profit. The idea was that each truck started distributing products to all customers and changed to a new one when it arrived at the decoupling point to minimize the cost for a longer journey. These two papers are good examples that demonstrate how to solve route construction with a vast number of customer nodes via the OVRP in the context of a classical supply chain. In contrast, to the best of our knowledge and according to the literature review, there is no information on how to implement the OVRP in the PI context.

As the distribution flow of the PI network should be continuously updated and synchronized, the concept of the simultaneous pickup and delivery problem (VRPSPD) with multiple depots and open routing must be considered. In this case, each customer is visited once, which can save more time for the pickup and delivery process. Moreover, pickup and delivery at the same time can help each PI-hub to manage the limited number of trucks and share them with other hubs. Several solving methods for the VRPSPD are presented in the next section.

2.2 Solving methods for the VRPSPD

Many studies have investigated the VRPSPD in the classical supply chain, but few studies deal with the PI context.

2.2.1 The VRPSPD in a classical supply chain. The survey of the VRPSPD (Parragh *et al.*, 2008) indicates that most of the research implemented tabu search (TS). The latter is one of the most popular metaheuristics proposed to solve the simultaneous pickup and delivery problem. As described in Boussaïd *et al.* (2013), the solution is chosen based on the tabu list to avoid difficulties finding a near-optimal solution at local minima. However, the computational time is longer compared with other methods such as local search (Bianchessi and Righini, 2007) or insertion-based heuristics (Montané and Galvão, 2006). Before implementing a solution, TS always checks existing solutions in the tabu list. Also, there is very little difference between the results of the TS and the other methods. Even though TS performs well to find a near-optimal solution, the performance of another metaheuristic known as “Simulated Annealing” is similar but does not consider previous solutions in the memory (Boussaïd *et al.*, 2013).

Simulated annealing (SA) can accept a worse solution but always accepts one that is better than the incumbent solution (Boussaïd *et al.*, 2013). SA is used for some VRPSPD problems. For example, the authors in Wang *et al.* (2015) demonstrated that SA provides shorter travel distances in around 36% of medium-size instances compared with a genetic algorithm based on the same number of vehicles. Also, the research by Yu and Lin (2015) showed that SA can obtain the same optimal solutions as CPLEX when there are less than 50 customers. The authors (Yu and Lin, 2016) highlighted that SA proposed a near-optimal solution compared with exact approaches. Mu *et al.* (2016) implemented parallel-SA with the datasets from Dethloff (2001), Salhi and Nagy (1999), and Montane and Galvao (Montané and Galvão, 2006). These different studies illustrate that the performance of SA is good in terms of total transport costs and computational time compared with other exact or metaheuristic methods.

2.2.2 The VRPSPD in the physical internet. Generally, regarding the vehicle routing problem in the PI context, most of the research is formulated and implemented using MILP (Caballini *et al.*, 2017; Fazili, 2014; Venkatadri *et al.*, 2016). However, some examples implemented metaheuristics to increase transportation efficiency. For instance, the authors in Pal and Kant (2016) proposed a genetic algorithm to maximize the number of products to be delivered and delivery quality of all fresh food transportation packages. Authors in

Ben Mohamed *et al.* (2017) formulated the simultaneous pickup and delivery problem in urban transportation using MILP. They improved the quality of the solution by implementing a constructive greedy heuristic as the initial solution and an insertion heuristic to reduce the postponement of non-service orders. However, they suggest ways of improving the solution using metaheuristic methods. Regarding all perspectives of the VRPSPD in previous studies, some exciting suggestions are proposed to improve future studies such as the implementation of metaheuristics, product delivery optimization and the real-case planning of transportation routes. A summary of existing studies is provided in Table 1.

According to the summary in Table 1, many studies have implemented exact and metaheuristic methods to solve the VRPSPD in the context of the classical supply chain. However, few studies have focused on the PI context. There are still some gaps in VRPSPD studies regarding the PI supply chain including focusing less on multiple depots and open routes for VRP. Therefore, these two aspects should be studied more in the PI context. The present paper provides some suggestions in this respect.

This study also mentions environmental sustainability through the calculation of total carbon emissions in the PI distribution network. Indeed, the concept of the PI not only improves the distribution performance but also focuses on the environmental impact (Montreuil *et al.*, 2013). Some relevant studies have proposed that the PI provides a good solution with respect to sustainability. For example, Pan *et al.* (2013) demonstrated that pooling in the supply chain network can reduce carbon emissions in road and rail transport modes. Another study (Yao, 2017) proposed that a one-stop delivery mode in online shopping could reduce unnecessary logistics activities for the transportation of goods from manufacturers to customers. The reduction in the transportation process between parties affects total carbon emissions in the network. These studies prove that PI has a positive impact on the environment. Details of all the relevant problems and assumptions regarding the transportation of goods are provided in the next section.

VRPSPD paper	Type of supply chain	Research context	Solving solution
Bianchessi and Righini (2007)	Classical	Heuristics for vehicle routing problem with simultaneous pickup–delivery	Tabu search, local search
Montané and Galvão (2006)	Classical	Tabu search with three types of movements: relocation, interchange, crossover	Tabu search, insertion-based heuristics
Yu and Lin (2016)	Classical	The location-routing problem with simultaneous pickup–delivery	Simulated annealing, Exact methods
Wang <i>et al.</i> (2015)	Classical	Parallel SA implemented for VRPSPD during specific time windows	Parallel SA, Exact method, Genetic Algorithm
Yu and Lin (2015)	Classical	A simulated annealing heuristic for the open location-routing problem	Simulated annealing, Exact method
Mu <i>et al.</i> (2016)	Classical	Parallel-SA implemented for VRPSPD with different datasets from Dethloff, Salhi and Nagy, and Montane and Galvao	Simulated annealing, parallel SA
Pal and Kant (2016)	Physical Internet	Proposed mechanism for decreasing empty truck miles and carbon footprint in a fresh food distribution network	Exact method, Genetic Algorithm
Ben Mohamed <i>et al.</i> (2017)	Physical Internet	Simultaneous pickup–delivery for interconnected city logistics	Exact method, insertion-based heuristics

Source(s): Authors own work

Table 1.
Summary of solving
solutions of the
VRPSPD

3. Problem statement and assumptions

This section presents the problem description and its assumptions in addition to the mechanism used to construct the feasible routes in both the classical and PI supply chains.

3.1 Assumptions

When the number of PI nodes is large, the set of connected routes between PI hubs and retailers is more complex. The problem assumptions then focus more on the route construction between PI hubs and retailers, pickup and delivery quantities, and infrastructure sharing in the network. The main assumptions used to construct the feasible routes in the next subsection (3.2) are as follows:

- (1) Different PI hubs can satisfy the stocks of retailers in the cluster, as depicted in the example in [Figure 1](#).
- (2) The transportation networks are constructed based on the connections between PI hubs and retailers and between retailers.
- (3) Trucks have time-window constraints during transportation in a day.
- (4) Each truck has to finish the simultaneous pickup and delivery within a day
- (5) Retailer demands are predicted from historical demands.
- (6) The delivery and pickup demands are equal or similar quantities ([Parragh et al., 2008](#))
- (7) Each hub has different holding costs. In fact, the holding cost of each hub is based on the distance and hub location. Moreover, in the experiment, the inventory capacity of each hub was limited so the goods distributed to each retailer did not exceed the maximum capacity, thus preventing the accumulation of goods at the end.

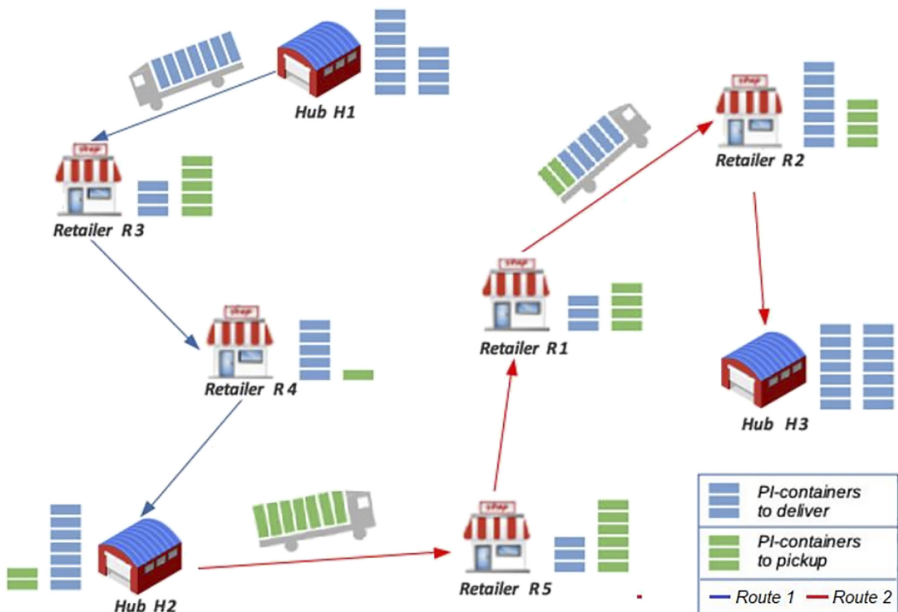


Figure 1.
Example of a PI network for the pickup and delivery problem with Route 1 and Route 2

Source(s): Authors own work

-
- (8) All PI-hubs can share their means of transportation (trucks, drivers) between them based on the number of PI hubs and retailers.
 - (9) PI hubs cover all retailer demands in a cluster.

3.2 The construction of feasible routes

As shown in the example in [Figure 1](#), the set of routes is based on the daily pickup and delivery demand of all retailers in a cluster. PI containers encapsulate all demands. The “PI containers to deliver” are considered as the new products to be distributed to customers, which are retailers in this case. In contrast, the “PI containers to pick up” are the returnable products such as product packaging or incompatible products which have to be returned to the PI hubs. The route starts from the starting hub to visit several retailers. After finishing all pickup and delivery processes, the last hub is assigned at the end of the route. This is a major difference with the classical supply chain, where all the trucks have to return to their starting point after finishing all transactions. In fact, as the PI context allows all PI hubs to share their resources in the network, a truck can go to the closest place after finishing its operation. Then, the end point can be the same as or different from the starting point. In addition, another difference between PI and classical is the open route and the dynamic interconnection between all nodes in the network. In [Figure 1](#) for Route #1 [H1-R3-R4-H2] in blue, the starting hub is H1 and the retailers are R3 and R4. The pickup and delivery process is completed simultaneously at each retailer. After completing all transactions, a truck transports the pickup PI containers to the last hub, H2. The concept of the pickup and delivery flow of Route #2 [H2-R5-R1-R2-H3] in red is the same as Route #1. However, the number of retailers visited is different because of the truck capacity and daily demand. All the details of our proposal, including the optimization models using both deterministic and heuristic methods, are presented in [section 4](#).

4. Solution approaches

Based on the assumptions and principles of route construction, this section proposes different approaches to construct feasible routes in each cluster. Firstly, the MIP model formulates the simultaneous pickup and delivery problem with relevant constraints in the PI context. Secondly, the route constructions are improved by the iterated random heuristic and metaheuristics proposed. For the metaheuristics, RLS and SA were chosen due to the shorter computational time and fast convergence. The SA acceptance criteria, including exponential and temperature, provide more flexibility for the acceptance solution. SA uses the exponential function which accepts various solutions at first and then becomes very selective when the temperature decreases. These methods were also benchmarked with an insertion heuristic method. An insertion heuristic is the improvement solution from the previous research ([Ben Mohamed et al., 2017](#)), which was a research work having a similar problem to our study. Since the insertion heuristic has provided better performance than others in the previous work, it would be a good indicator to implement and compare the performance with other methods in this study. Thirdly, the results are compared with the MIP model and metaheuristics in terms of the total distribution cost and computational time. As the PI network prioritizes sustainability and full collaboration in the transportation network, calculation of CO₂ emissions and the concept of infrastructure sharing would imply sustainability and cost optimizing perspectives. Furthermore, this work focuses on multiple depots and open vehicle route construction between hubs and retailers in the PI context. The model proposed in this paper is a new approach in the PI context, which is not addressed in the literature. Heuristics methods are used to solve the large size of problem in this paper in a reasonable time.

4.1 Mixed integer programming (MIP) model

This model is inspired by the MDVRP in [Montoya-Torres et al. \(2015\)](#) and [Montoya-Torres et al. \(2016\)](#) to solve the transportation routing problem between PI hubs and retailers. However, some new constraints and variables have been added to support the simultaneous pickup and delivery process in the context of the PI. In fact, in previous studies, the developed model did not take into account the constraints of the PI paradigm, such as sharing both storage and transportation resources. This problem is defined over a graph $G = (V, A)$ where V is the hub and retailer nodes, and A is the set of arcs between the nodes. The calculation of the holding cost was inspired by [Yang et al. \(2017\)](#). The following mathematical model was used:

Notations:

- H number of PI hubs
- R number of retailers
- K number of trucks
- N number of pickup and delivery points, which are PI hubs and retailers
- Speed truck speed (km/h)
- Driving_hr driving hours in a day
- $d1_{ij}$ distance matrix from retailer i to retailer j
- $d2_{hi}$ distance matrix from hub h to retailer i
- S_h initial inventory levels at hub h
- INC_h inventory unit cost at hub h
- $D1_i$ delivery demand at retailer i
- $D2_i$ pickup demand at retailer i
- T_k capacity of truck k
- TC fixed unit transportation cost per kilometer

Decision variables:

- Y_{hik} 1, if vehicle k goes from hub h to retailer i . 0, otherwise
- X_{ijk} 1, if vehicle k goes from retailer i to retailer j . 0, otherwise
- Z_{ihk} 1, if vehicle k goes from retailer i to hub h . 0, otherwise
- q_{nk} loading quantity of truck k after visiting pickup and delivery point n
- pos_{nk} position of truck k at pickup and delivery point n
- Inv_h remaining inventory levels at hub h after distributing goods to all pickup and delivery points
- Starting_ p_k starting point of truck k
- Ending_ p_k end point of truck k
- qp_{hk} loading quantity of truck k at starting hub h

The objective of this model is to minimize the total cost by respecting the following constraints:

Min:

$$\begin{aligned}
 TC \cdot & \left(\left(\sum_{h=1}^H \sum_{i=1}^R \sum_{k=1}^K d2_{hi} \cdot Y_{hik} + \left(\sum_{i=1}^R \sum_{j=1}^R \sum_{k=1}^K d1_{ij} \cdot X_{ijk} \right. \right. \right. \\
 & \left. \left. \left. + \left(\sum_{h=1}^H \sum_{i=1}^R \sum_{k=1}^K d2_{hi} \cdot Z_{ihk} \right) \right) + \sum_{h=1}^H (INC_h \cdot Inv_h) \right) \tag{1}
 \end{aligned}$$

Subject to:

Multiple-depot
vehicle routing
problem in
the PI

$$R \cdot \sum_{h=1}^H \sum_{i=1}^R Y_{hik} \geq \sum_{i=1}^R \sum_{j=1}^R X_{ijk}, \forall k \{1, \dots, K\} \quad (2)$$

$$R \cdot \sum_{h=1}^H \sum_{i=1}^R Z_{ihk} \geq \sum_{i=1}^R \sum_{j=1}^R X_{ijk}, \forall k \{1, \dots, K\} \quad (3)$$

$$\sum_{h=1}^H \sum_{k=1}^K Y_{hik} + \sum_{j=1}^R \sum_{k=1}^K X_{jik} =, 1 \forall i \{1, \dots, R\} \quad (4)$$

$$\sum_{h=1}^H Y_{hik} + \sum_{j=1}^R X_{jik} = \sum_{h=1}^H Z_{ihk} + \sum_{j=1}^R X_{ijk}, \forall k \{1, \dots, K\}, \forall i \{1, \dots, R\} \quad (5)$$

$$X_{iik} = 0, \forall k \{1, \dots, K\}, \forall i \{1, \dots, R\} \quad (6)$$

$$U_i - U_j + R \cdot X_{ijk} \leq R - 1, \forall k \{1, \dots, K\}, \forall i, j \{1, \dots, R\} \quad (7)$$

$$q_{0k} \leq T_k, \forall k \{1, \dots, K\} \quad (8)$$

$$q_{0k} = \left(\sum_{i=1}^R \sum_{h=1}^H D_{li} \cdot Y_{hik} \right) + \left(\sum_{i=1}^R \sum_{j=1}^R D_{lj} \cdot X_{ijk} \right) \quad (9)$$

$$X_{0jk} = \sum_{h=1}^H Y_{hjk}, \forall k \{1, \dots, K\}, \forall j \{1, \dots, R\} \quad (10)$$

$$pos_{1k} = \sum_{j=1}^R j \cdot X_{0jk}, \forall k \{1, \dots, K\} \quad (11)$$

$$(pos|nk = j) = pos_{n+1,k} = \sum_{i=1}^R i \cdot X_{ijk}, \forall k \{1, \dots, K\}, \forall j \{1, \dots, R\}, \forall n \{1, \dots, N-1\} \quad (12)$$

$$(pos|nk = 0) = pos_{n+1,k} = 0, \forall k \{1, \dots, K\}, \forall n \{1, \dots, N-1\} \quad (13)$$

$$(pos|nk = j) = q_{nk} = q_{n-1,k} + (D_{2j} - D_{1j}), \forall k \{1, \dots, K\}, \forall j \{1, \dots, R\}, \forall n \{1, \dots, N\} \quad (14)$$

$$(pos|nk = 0) = q_{nk} = 0, \forall k \{1, \dots, K\}, \forall n \{1, \dots, N\} \quad (15)$$

$$q_{nk} \leq T_k, \forall k \{1, \dots, K\}, \forall n \{1, \dots, N\} \quad (16)$$

$$(Y_{hik} = 1) = Starting_{pk} = h, \forall k \{1, \dots, K\}, \forall i \{1, \dots, R\}, \forall h \{1, \dots, H\} \quad (17)$$

$$(Z_{ihk} = 1) = Ending_{pk} = h, \forall k \{1, \dots, K\}, \forall i \{1, \dots, R\}, \forall h \{1, \dots, H\} \quad (18)$$

$$(Starting_{pk} = h) = qp_{hk} = q_{0k}, \forall k \{1, \dots, K\}, \forall h \{1, \dots, H\} \quad (19)$$

$$(Starting_{pk} \neq h) = qp_{hk} = 0, \forall k \{1, \dots, K\}, \forall h \{1, \dots, H\} \quad (20)$$

$$S_h \geq \sum_{k=1}^K qp_{hk}, \forall h \{1, \dots, H\} \quad (21)$$

$$\text{Inv}_h = S_h - \sum_{k=1}^K q_{pk}, \forall h \{1, \dots, H\} \quad (22)$$

$$\left(\sum_{h=1}^H \sum_{i=1}^R d_{2_{hi}} \cdot Y_{hik} + \sum_{i=1}^R \sum_{j=1}^R d_{1_{ij}} \cdot X_{ijk} + \sum_{h=1}^H \sum_{i=1}^R d_{2_{hi}} \cdot Z_{ihk} \right) / \text{Speed} \leq \text{Driving}_{hr}, \quad \forall k \{1, \dots, K\} \quad (23)$$

$$\text{Starting}_{pk} = \text{Ending}_{pk}, \forall k \{1, \dots, K\} \quad (24)$$

In the MIP model, [equation \(1\)](#) represents the objective function; it minimizes the total transportation cost from hub to retailer, retailer to retailer, and retailer back to the hub, and includes the total holding cost after finishing distributing goods. [Equations \(2\) and \(3\)](#) denote that every route should start and finish at a hub. The starting hub and end hub can be the same or different. [Equation \(4\)](#) denotes that all retailers must be visited once. [Equation \(5\)](#) presents the flow of goods between hubs and retailers. [Equation \(6\)](#) states that the vehicle must move from one retailer to another retailer or the end hub. [Equation \(7\)](#) eliminates sub-tours in each route. This equation is inspired by [Montoya-Torres et al. \(2016\)](#). [Equations \(8\) and \(9\)](#) denote that the initial quantity at the first node must be equal to the total demand of all retailers along a route. They need to respect the truck capacity. [Equation \(10\)](#) states that the status of vehicle k at the first node on each route is constructed from the starting hub to the first retailer. [Equations \(11\) to \(13\)](#) describe the position of a retailer along a route. The maximum number of retailers for each route is based on the truck capacity. The loading quantity of each truck is calculated after visiting pickup and delivery point n . [Equation \(14\)](#) expresses that the total loading quantity at the delivery–pickup point n should respect the truck capacity. [Equation \(15\)](#) expresses that the total loading quantity will no longer be updated after visiting all retailers. [Equations \(16\) to \(18\)](#) denote that the starting point of each route is the starting hub, and the end point is the end hub after visiting all the retailers on the route. [Equations \(19\) to \(21\)](#) initialize the loading quantity of each truck before leaving the starting hub. The total loading quantity of all trucks should respect the inventory level at the starting hub. [Equation \(22\)](#) proposes updating inventory levels after distributing goods to retailers on all routes. Lastly, [equation \(23\)](#) proposes that the total driving time of each truck should respect the maximum number of driving hours in a day. In addition, there is another constraint to specify the difference between the PI and a classical distribution network. [Equation \(24\)](#) proposes that each truck must return to the initial hub after finishing all deliveries at retailers. This situation only happens in the classical distribution network.

After formulating the problem using MIP, a random local search is proposed to solve the problem due to high computational times in CPLEX. It is important to highlight that the objective of this CPLEX experiments is to only validate the model and make sure all the constraints are correctly implemented and verified. Moreover, the optimal values will help compare the performance of the suggested meta-heuristics. All the details are provided in the next section.

4.2 Random local search (RLS)

This method, inspired by [Kantasa-ard et al. \(2021a\)](#), is proposed to improve the initial solution. Once generated, the initial solution is improved by local search moves. In this study, two local search moves are considered: insertion and swap. With insertion, a random retailer is selected from a different random route then inserted in the best position of the chosen route without exceeding the truck capacity. With swapping, two random retailers are selected from different routes then swapped after verifying the truck capacity constraint. These two local

search moves are made at each iteration with the same probability ($p = 0.5$). In addition, swap or insertion moves are selected randomly. These moves generate more efficient solutions and provide good results with a shorter computational time. The improvement solution from Ben Mohamed *et al.* (2017) is similar to this method. However, the existing one only focuses on the insertion move. After finishing the local search, the new solution S' is compared with the existing solution. Let us suppose that the new solution provides a lower distribution cost than the existing solution, it will then replace and update the existing ones. Otherwise, the proposed solution is rejected, and the local search will continue until all iterations have been completed. The flow chart of this solution is shown in Figure 2.

Based on the above solution, the solution is improved and presents the total distribution cost, particularly with large instances. SA is also proposed to improve solution performance and is described in the next section.

4.3 Simulated annealing (SA)

The process of the SA proposed is similar to a RLS. However, there are some differences as highlighted by the proposed heuristic in Figure 2. Firstly, SA requires an initializing temperature (T) before starting the local search. Secondly, there are two possibilities of accepting the new solution after finishing the local search. If the new solution provides a lower distribution cost than the existing solution, the solution will be updated. Otherwise, the new solution will be accepted with the probability $p(T, f(S'), f(S))$ depending on the temperature T and a random value between 0 and 1. After a certain number of iterations, the temperature is reduced. This metaheuristic will continue to find a suitable solution until the temperature equals zero. The details are presented in Figure 3.

5. Experimental results: case study

5.1 The distribution process of agricultural products in Thailand

Recently, many studies have implemented new technologies and innovative methods to enhance the performance of agriculture supply chains (Lezoche *et al.*, 2020; Mejjauoli and Babiceanu, 2018; Panetto *et al.*, 2020). However, few studies have focused on the distribution process of agricultural products, especially in Thailand.

For instance, the research by Chiadamrong and Kawtummachai (2008) implemented MIP and a genetic algorithm to define the best inventory position and transport route for the sugar export process. Timaboot and Suthikarnnarunai (2017) formulated linear programming to minimize total transportation costs in the cassava supply chain. Finally, Luangpaiboon, (2017) proposed an alternative solution to minimize the imbalance of truckloads such as no-back load or delayed pickup and delivery on multi-zone dispatching of One Tambon One Product (OTOP) products in Thailand.

These studies focused mainly on the pickup and delivery process in the classical supply chain and formulated the problem based on MIP models. However, there are no relevant studies in the PI context. Due to the research gaps mentioned earlier, the concept of VRSPD was implemented in the PI context with the dataset of customer demand for agricultural products in Thailand.

5.2 Dataset

The forecast of daily demand in tons for each retailer was randomly generated from the total predicted daily data of agricultural products in the northern region of Thailand (Kantasa-ard *et al.*, 2021b). The demand interval of each retailer was the range 15–30 tons, and the stock interval of each hub was the range 50–100 tons. In this case, a single agricultural product, pineapple, was considered. For the delivery process, PI containers distribute new pineapples

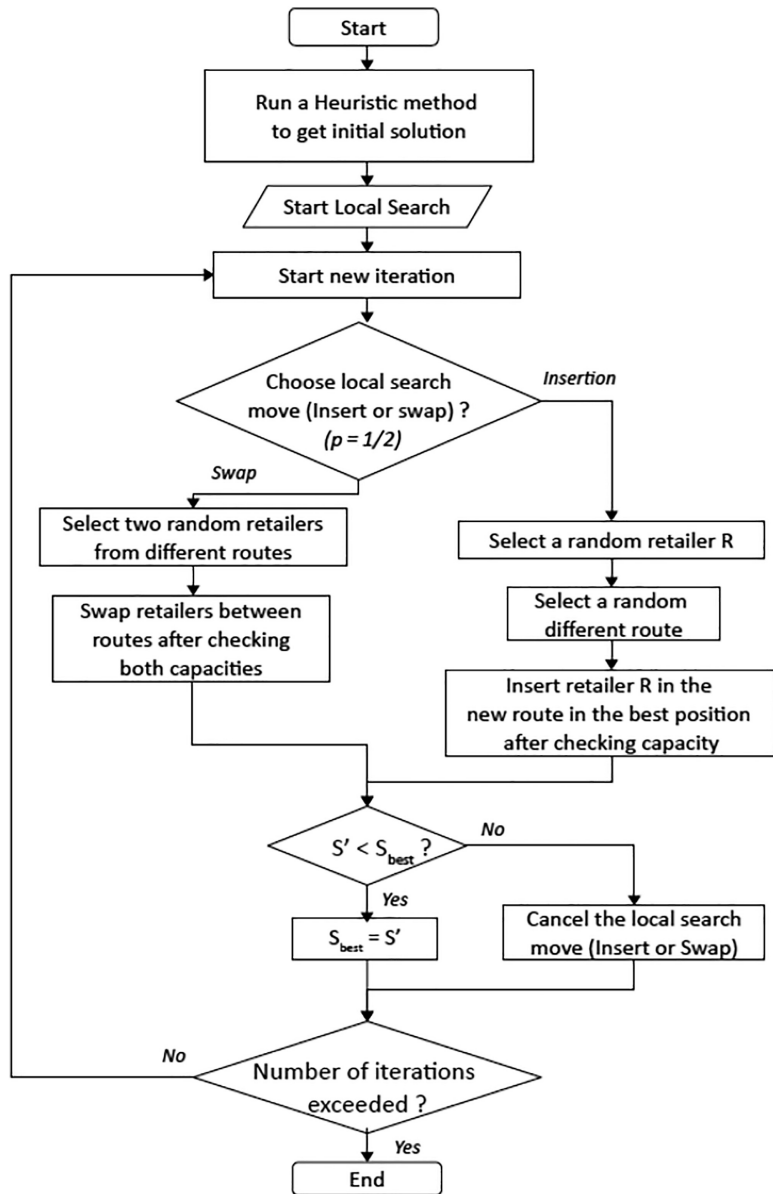
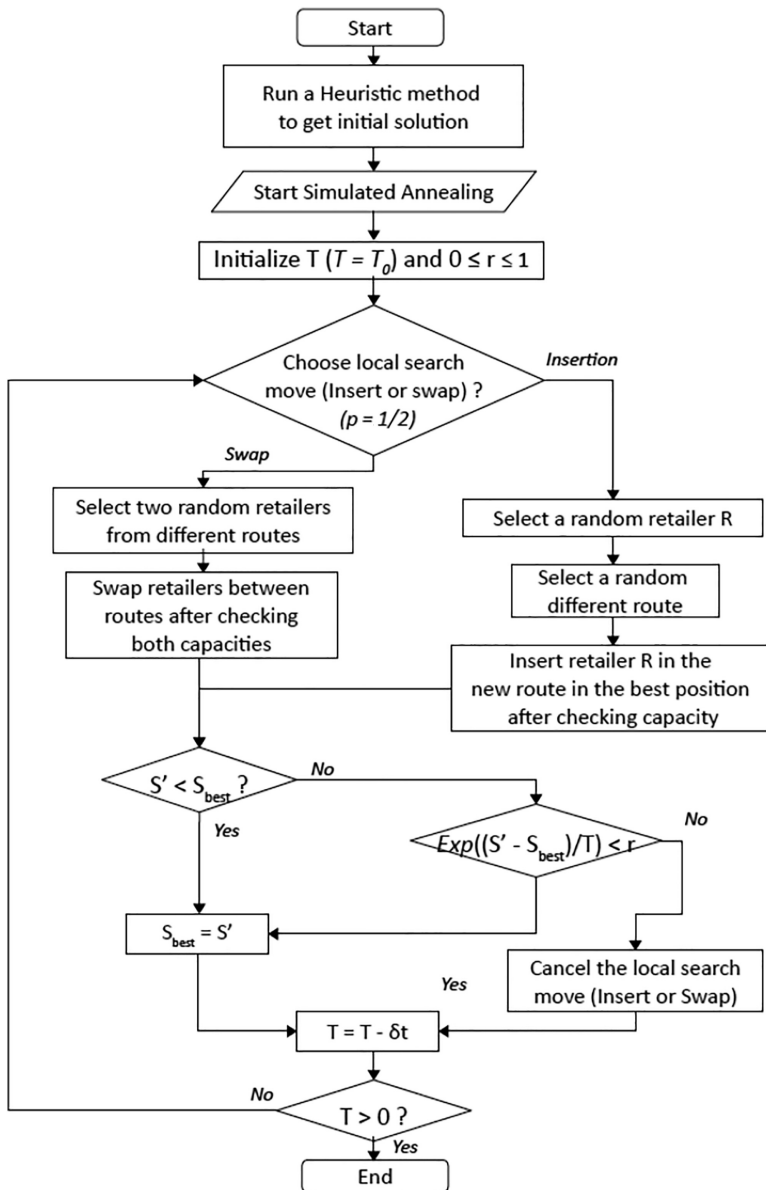


Figure 2.
The random local search process

Source(s): Authors own work

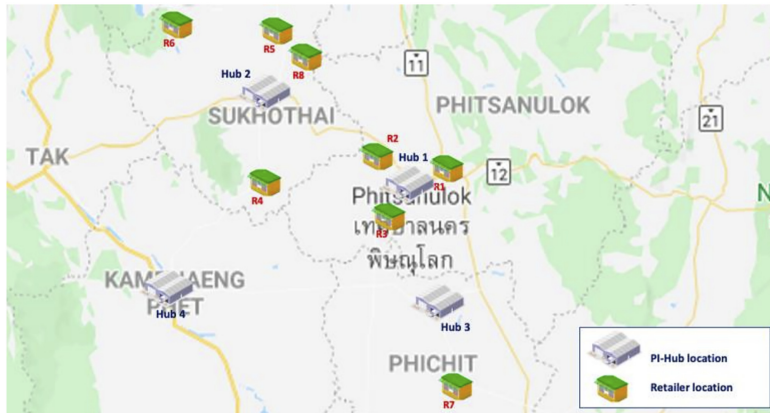
to retailers. For the pickup process, PI containers pick up some overripe pineapples and take them back to PI hubs. Accurate positions of the PI hubs and the retailer were established in the main cities and some random supermarkets in the northern region based on the positions in Google Maps, as shown in Figure 4. The unit price of transportation was equal to €0.053



Source(s): Authors own work

Figure 3.
The simulated
annealing process

(Kantasa-ard *et al.*, 2021b). The unit holding cost, which was inspired by Kantasa-ard *et al.* (2021b), was equal to [5.2, 2.6, 1.3] euros for all hubs based on the location of each hub. The fuel emission rate (FE) was 2,621 g/l, and the fuel consumption rate (FC) was 0.3462 l/km based on a 70%–80% load in rural areas (Hoen *et al.*, 2014). The total distance (D) was the main input factor to calculate total carbon emissions. In this study, the total distance was the sum of the



Source(s): Authors own work

Figure 4.
Example of PI hub and
retailer locations

total distance from hubs to retailers and retailers to retailers. The formula of total emissions was inspired by [Hoen et al., 2014](#)):

$$EM_{total} = FE * FC * D \tag{25}$$

This model was validated using IBM CPLEX (Version 12.8) for the exact method and java programming language for the heuristic and metaheuristic methods on an Intel Core i5 CPU with 4 GB of DDR3 RAM. The global time limit in CPLEX was 7,200 s. For the metaheuristics, the tests were replicated five times and the average values are presented.

According to the background and dataset of the case study, the results of each model, including the performance comparisons between the classical supply chain and PI, are presented in the results analysis and discussion section.

5.3 Results analysis and discussion

Ten scenarios with different PI hubs and retailers are considered in [Table 2](#). They were implemented to calculate the total distribution cost in this model, which is the summation of the total transportation and holding costs. The total carbon emissions were also considered in this experiment. These scenarios were tested using MIP and the two metaheuristics presented previously.

Scenario	Number of hubs	Number of retailers	Number of trucks
1	2	4	2
2	3	6	3
3	3	8	4
4	3	12	6
5	4	8	4
6	4	12	6
7	6	12	6
8	6	18	12
9	6	24	12
10	8	24	12

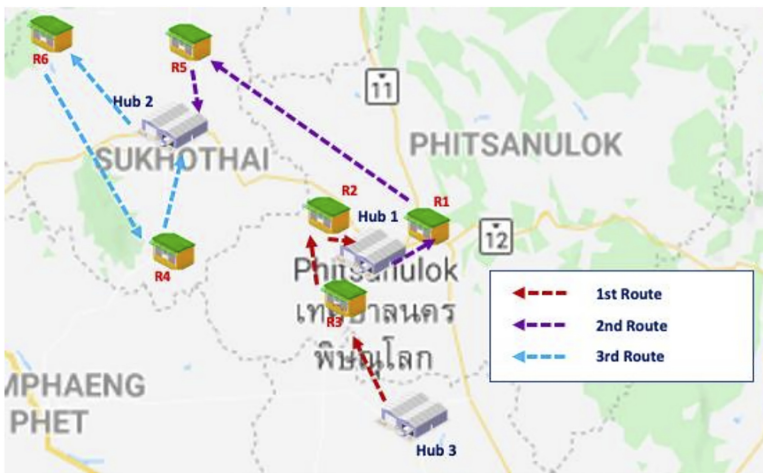
Table 2.
Parameter values
in all scenarios

Source(s): Authors' own work

Each route comprises the starting hub, retailers and the last hub. As introduced in the assumptions, the starting hub prepares each truckload with full containers and the last hub unloads all pickup containers from a truck. The MIP model formulates the solution obtained. In the example with scenario 2, as shown in Figure 5, there are three routes in a cluster with one truck per route based on the truck capacity and retailer demand. The first route is [H3-R3-R2-H1], the second route is [H1-R1-R5-H2] and the third route is [H2-R6-R4-H1].

As seen with the above routes, there are two possibilities. The starting hub and the last hub are identical or different based on the distance between the last hub and the last retailer. Moreover, all metaheuristics include the iterated random heuristic as an initial solution. The simulation results are presented in Table 3, and Figures 6 and 7 below.

As shown in Table 3 and Figure 6a, the total PI distribution cost was lower with the MIP model in CPLEX than the other methods for scenarios 1 to 6. However, MIP shows higher cost



Source: Authors own work

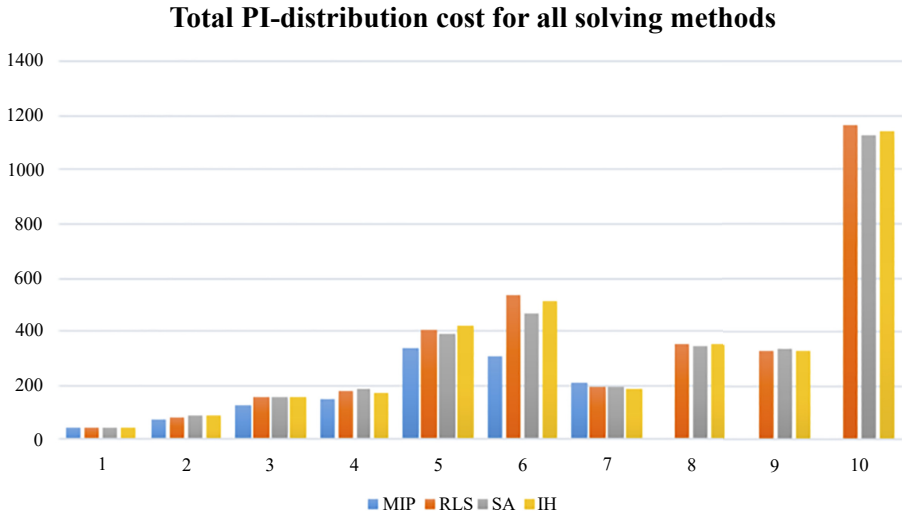
Figure 5.
Example of
transportation routes
between PI hubs and
retailers

Sc	Total PI-distribution cost						Insertion heuristic (Ben Mohamed <i>et al.</i> , 2017)				
	PI	MIP	%GP	PI	RLS	%GP	PI	SA	%GP	PI	%GP
1	41.3	0		43.0	4.1		42.1	1.9		43.0	4.1
2	76.3	0		81.2	6.4		91.2	19.5		90.1	18.1
3	127.8	0		159.1	24.5		160.1	25.3		160.1	25.3
4	149.5	0		177.0	18.4		185.5	24.1		170.9	14.3
5	339.3	0		402.0	18.5		390.7	15.1		419.1	23.5
6	308.1	0		529.9	72.0		467.2	51.6		513.1	66.5
7	206.7*	0		194.7	5.8		191.4	7.4		189.4	8.4
8	-	-		355.8	N/A		345.0	N/A		352.5	N/A
9	-	-		331.0	N/A		340.9	N/A		331.7	N/A
10	-	-		1164.4	N/A		1124.4	N/A		1140.7	N/A

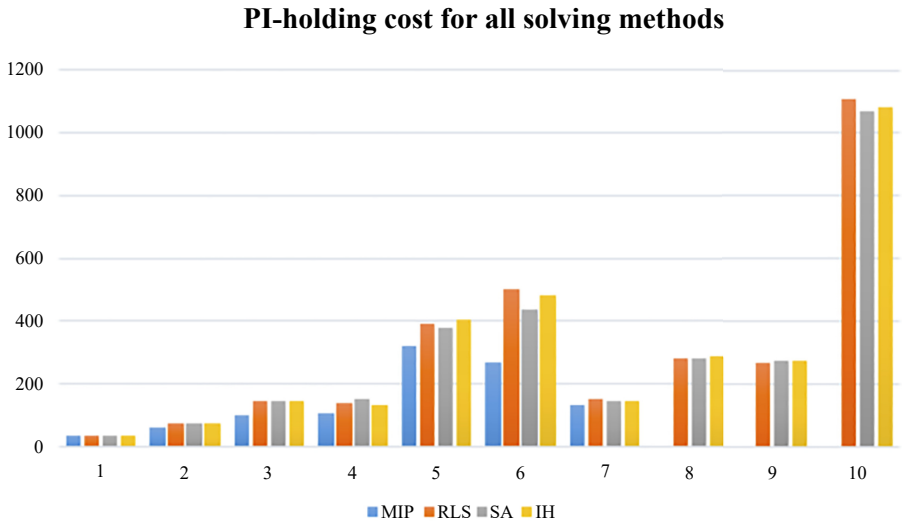
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%GP is the gap between metaheuristics and the optimal solution using MIP

Table 3.
Comparison of the total
costs and gap
percentage between
MIP and
metaheuristics in the PI
context



(a)

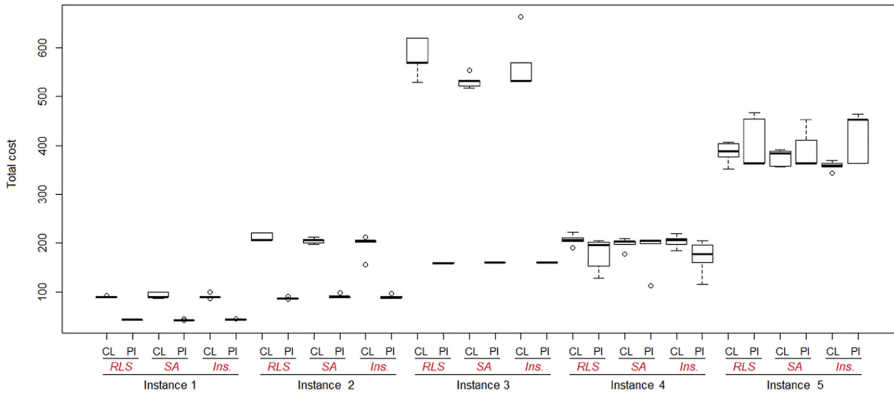


(b)

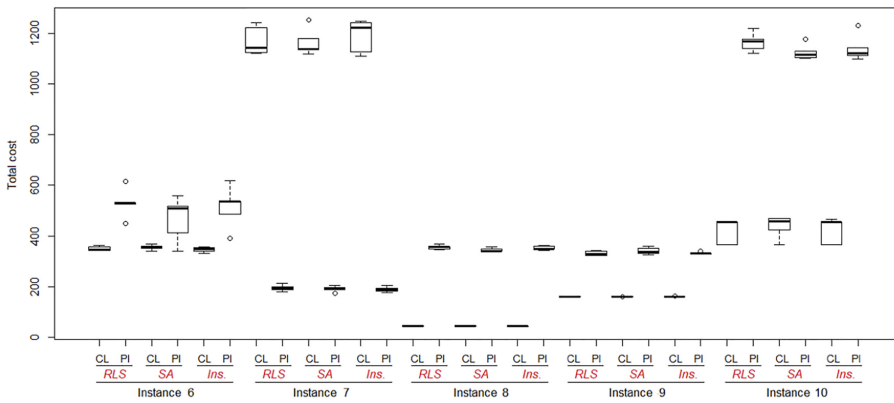
Figure 6. Comparison of total costs with MIP, RLS, SA and an insertion heuristic in the PI context (6 A-B)

Source(s): Authors own work

than heuristic algorithm in scenario 7. The reason is that MIP could not find an optimal solution within 7,200 s, which is the maximum global time. In addition, due to the global time limit, CPLEX cannot run large instances (scenarios 8 to 10). In this case, we assessed the performance using metaheuristics. Based on three scenarios (8–10), SA provided the best performance in terms of the total distribution cost. When we consider a sub-cost within the total distribution cost (holding cost (6 B), for example), SA also provided a lower holding cost than the other methods. The average difference between SA and MIP was around 21% for the



(a)



(b)

Source(s): Authors own work

Figure 7.
The five replications
for each instance and
each metaheuristic for
the total distribution
cost (7 A-B)

total distribution cost. The MIP model can solve the problem in small-to-medium instances, as shown in scenarios 1 to 7, while SA can solve the problem in large instances, as shown in scenarios 8 to 10. It is important to mention that in this study, we focus more on solving the model with meta-heuristics in a reasonable time. The complexity of the model makes it hard to find a lower bound for this model.

In addition, the results for all the metaheuristics are represented by the average values of five replications for each instance, as shown on the box plot graph in Figure 7. Indeed, Figure 7a presents the results of the RLS, SA and insertion heuristic for instances 1 to 5, and Figure 7b presents the results for instances 6 to 10. The results show that all the metaheuristics provide long-lasting results for most of the instances. Moreover, the total distribution costs in the PI context are mostly lower than the classical supply chain.

Regarding Table 4 and Figure 8 below, the performance of the MIP model and the metaheuristics were evaluated with three random instances. These instances show that the MIP model still provided a lower total PI distribution cost. Additionally, SA outperformed the other metaheuristics and differed little from the MIP model. Moreover, these instances prove that the average number of retailers per route can be more than two. Some trucks

contained the requests of three retailers, and some contained the requests of only one retailer. The number of retailers per truck varied due to the difference in retailer demand.

In terms of the computational time, even though the MIP model provides the optimal total distribution cost in these cases, it takes longer when the number of hubs and customers increases. As shown in Table 5, it takes approximately 5 s for a small number of PI nodes and more than 7,200 s for a large number of PI nodes to obtain the optimal result in some scenarios. In contrast, other metaheuristics propose a solution in less than one second.

Table 4.
Parameter values for
random instances

Scenario	Number of hubs	Number of retailers	Number of trucks
R1	3	6	2
R2	4	12	5
R3	3	8	3

Source(s): Authors own work

Figure 8.
Comparison of total PI
distribution cost with
random instances

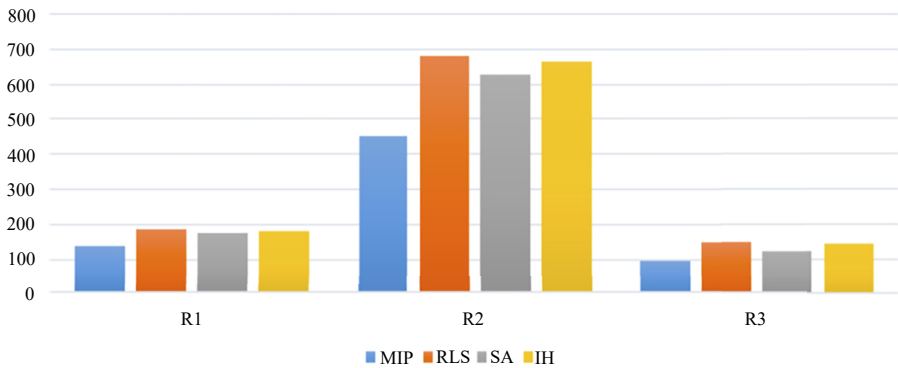


Table 5.
Comparison of the
computational times
between a classical
supply chain and PI
with MIP, RLS, SA and
insertion heuristic
methods

Sc	Computational time (seconds)						Insertion heuristic (Ben Mohamed <i>et al.</i> , 2017)	
	MIP		RLS		SA		Classical	PI
	Classical	PI	Classical	PI	Classical	PI	Classical	PI
1	3.73	3.73	0.010	0.012	0.011	0.011	0.007	0.007
2	3.24	3.00	0.015	0.010	0.015	0.013	0.008	0.011
3	3,120	3,120	0.013	0.009	0.017	0.019	0.010	0.011
4	7,200	7,200	0.001	0.001	0.014	0.014	0.010	0.007
5	1800	1884	0.021	0.013	0.035	0.027	0.051	0.019
6	3,600	7,200	0.021	0.013	0.015	0.054	0.025	0.017
7	7,200	7,200	0.019	0.012	0.001	0.009	0.008	0.018
8	7,200	7,200	0.090	0.226	0.213	0.134	0.174	0.068
9	7,200	7,200	0.075	0.156	0.158	0.109	0.127	0.174
10	7,200	7,200	0.075	0.075	0.082	0.065	0.073	0.116

Source(s): Authors' own work

Additionally, some scenarios run out of memory due to there being too many retailers. Therefore, it could be better to implement heuristic and metaheuristic methods to minimize the total distribution cost when retailers and hubs are increased.

For the total CO₂ emissions in Table 6 and Figure 9, the carbon emissions were calculated from the total transportation cost. Most PI cases provided lower carbon emissions than the classical supply chain. After comparing metaheuristics, SA provided the lowest carbon emissions with 84.23 kg in the first instance and 1013.78 kg in the last instance. This means that route construction within the context of the PI is more sustainable and more environmentally friendly.

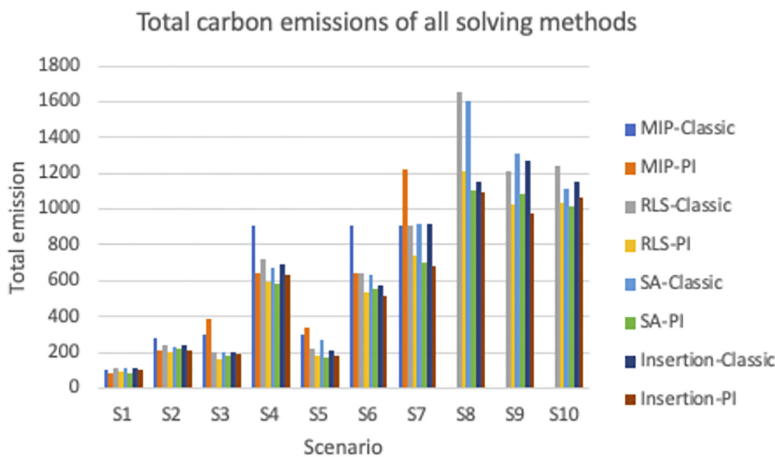
6. Managerial insights

Regarding all the previous results, we demonstrate the performance of PI distribution in terms of the VRPSPD. All performance indicators (i.e. total distribution cost, computational

Sc	Total emissions (kg)							
	MIP		RLS		SA		Insertion heuristic (Ben Mohamed <i>et al.</i> , 2017)	
	Classical	PI	Classical	PI	Classical	PI	Classical	PI
1	105.052	83.206	109.880	95.704	114.639	84.233	109.880	103.169
2	280.709	214.829	235.956	201.783	234.038	221.814	240.886	211.918
3	296.939	384.425	204.385	164.460	201.441	181.444	201.715	190.346
4	910.318	644.898	719.098	595.043	676.434	585.147	691.123	629.318
5	296.939	334.245	220.239	179.081	268.416	172.681	213.802	186.169
6	910.318	644.898	646.610	533.545	632.811	556.008	570.800	517.521
7	902.887*	1224.600*	910.129	742.005	915.437	703.176	919.272	682.871
8	–	–	1656.997	1208.507	1607.724	1107.427	1153.207	1093.251
9	–	–	1210.253	1023.639	1308.251	1086.608	1271.442	978.646
10	–	–	1245.179	1034.973	1118.544	1013.777	1157.316	1060.893

Source(s): Authors' own work

Table 6.
CO₂ emissions in a classical supply chain and PI with MIP, RLS, SA and insertion heuristic methods



Source(s): Authors own work

Figure 9.
CO₂ emissions in a classical supply chain and PI using MIP, RLS, SA and insertion heuristic methods

time and total CO₂ emissions) can help supply chain managers make better decisions and manage the relevant resources easily in the PI distribution network. In addition, we would like to propose the managerial flow as a framework for PI transportation and inventory planning. This framework will increase resource planning flexibility in the supply chain.

As illustrated in the managerial flow chart in Figure 10, our proposed metaheuristic will be implemented in a decision support system (DSS). Firstly, the forecast data are transferred from PI hubs and retailers to the DSS. Then, supply chain managers can make the operational decisions in the PI network using this system. The feasible transportation route and total distribution cost are the primary outputs using the MIP model in CPLEX or metaheuristics.

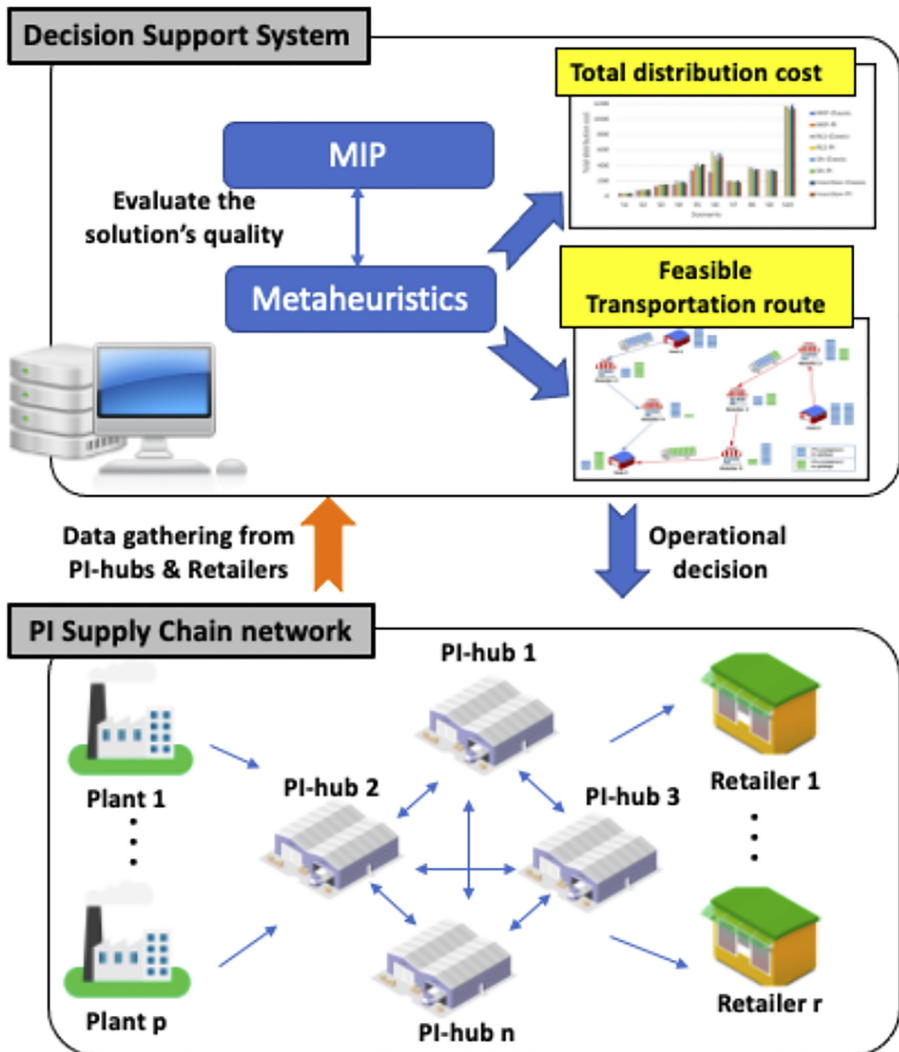


Figure 10. Overview of the managerial flow in the supply chain

Source(s): Authors own work

Regarding the metaheuristics, SA was chosen due to its outstanding performance (total cost and computational time). The DSS chooses the MIP model or metaheuristic based on the evaluation of the quality of the solution and the size of the instances. The quality of the solution is a trade-off between total distribution cost and computational time. This flow chart can be adapted and applied to other case studies.

7. Conclusion

This study proposes two main approaches. Firstly, a mathematical model was proposed to formulate the simultaneous VRPSPD in the PI. Secondly, metaheuristics, in this case RLS and SA, were proposed to improve the transportation routing solution. These approaches were compared with the classical supply chain network with the same case study. The results show that for many instances the total distribution cost is lower in the PI context than in the classical supply chain. MIP provides the best results for small and medium instances (scenarios 1 to 6). Metaheuristics provide suitable results for large instances (scenarios 8 to 10) with a shorter computational time. Moreover, the SA implemented demonstrates the best results in terms of total distribution cost and holding cost. For the transportation cost, the performance was quite close to the insertion heuristic method. The average difference between SA and MIP was around 14% for the total distribution cost and 20% for the holding cost. For the total carbon emissions, the PI concept proposed a better solution than the classical supply chain with lower carbon emissions. For example, SA provided the lowest carbon emissions with 84.23 kg in the PI network, while the classical network exploded with 114.64 kg of carbon in the same instance. In addition, we demonstrated how to implement the MIP and metaheuristics to optimize all relevant costs in the decision support system.

Regarding future aspects, this research can be improved by implementing another metaheuristic as a benchmark. Furthermore, all PI hubs should have the same number of trucks before continuing transportation the next day. This problem hypothesis concerns both PI and classical networks. Additionally, our approaches can enhance the potential of product planning and distributing both operational and managerial aspects in many fields, not only agricultural products. If the distribution network is more complex than our experiment, our approaches can still be helpful to implement and reduce the network's complexity. Researchers can also consider sustainability by implementing another type of transportation such as an electric truck or train and considering multimodal transportation to reduce total carbon emissions.

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