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The Impacts of the Cross-Chain Collaboration Center Model on Transportation Performance: A Case Study of a Bulk Transportation Network in Thailand

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ABSTRACT This paper studies the impacts of a cross-chain collaboration center model (4CM) on bulk transportation network performance. The 4CM is based on the interaction and collaboration between shippers and carriers participating in the transportation network. The network formulation is based on collaborative bidirectional multi-period vehicle routing (CBMVRP). The performance of the 4CM is represented by three transportation performance indices, including the percentage differences in the total cost, shipper cost and carrier cost between the 4CM and single-chain collaboration model (SCCM). The impacts of the 4CM are investigated using five uncertain input parameters: fuel cost, holding cost, maximum acceptable proportion of the differences between the cost of a carrier and average cost of all carriers, demand per job and number of vehicles per carrier. An experiment was conducted according to a central composite design (CCD). The proposed methodology was applied to assess bulk transportation in Thailand. The computational results revealed that a 4CM can significantly reduce the differences in the total cost, shipper cost and carrier cost. Moreover, we organized a focus group to collect data about the criteria and the probability of changing from an SCCM to a 4CM of the case study network and generated a classification tree of the levels of possibility to change from an SCCM to a 4CM for each possible situation using the ID3 algorithm.

INDEX TERMS Collaborative vehicle routing, full truckload transportation, collaborative transportation management, opportunity levels to implement a cross-chain collaboration.

I. INTRODUCTION

The bulk transportation problem is one in which a specific number of full truckloads must be transported from one terminal to another in the shortest possible time. Bulk goods are often raw materials in very large quantities, making it difficult to complete the work within short time periods. Many manufacturers outsource their logistics activities by hiring shippers to improve their transportation efficiency, resulting in an increased number of outsourcing firms [1]. The shipper that receives a job from the customer needs to use vehicles from various carriers to meet the relevant demands. However, the failure rate of logistics outsourcing remains high [2]. The major problem for every organization is that transportation costs and competition rates tend to increase every year, causing many small companies to close down their businesses. For the above reasons, many transportation chains use collaborative transportation management (CTM) to provide flexibility in the physical distribution and improve transportation efficiency [3]. In particular, repositioning costs and empty mileage can be avoided, leading to better transportation performance overall. Although CTM offers undeniable benefits, it also requires a high degree of mutual trust among the various parties who must work together to achieve

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those benefits [4]. From the perspective of trust, it is necessary to develop an independent transportation control scheme that allows impartial decisions to meet the requirements of the customers and balance the interests of the cooperating logistics providers who must deliver the service. The control scheme thus facilitates collaboration among the various parties involved in the supply chain. It is important that the transport control tower derives no particular benefit from the plans they issue, and hence, efficiency and fairness can be guaranteed. This approach ensures that all parties are treated equally and that data protection is maintained for the privacy of all involved parties. These control towers are used at all levels of CTM, which results in relatively straightforward collaboration among parties. The control tower is also an important part of a cross-chain collaboration center (4C). A 4C is the control center that brings together the latest techniques, advanced software concepts, and supply chain experts. Moreover, the 4C enables collaboration across various supply chains, thereby enhancing the transport capacity of interoperable networks and enabling collaborative decision-making [5]. It is clear that a 4C is the best way to increase the overall benefit and reduce CO_2 emissions in multiple supply chains [5]–[6]. In addition, collaboration for integrated supply chains can also enable distributing humanitarian aid postdisaster [7]–[8]. The acronyms in this research are as follows.

- 4C: Cross-chain collaboration center
- 4CM: Cross-chain collaboration center model
- SCCM: Single-chain collaboration model
- CTN: Collaborative transportation network
- CTM: Collaborative transportation management
- CBMVRP: Collaborative bidirectional multi-period vehicle routing problem
- ILP: Integer linear programming
- CCD: Central composite design
- SOC: Study opportunities to increase the level of collaboration for each possible situation
- IFT: Investigating the effect of critical factors on transportation performance
- NC: Noncollaboration
- CO: Collaboration for a single supply chain
- GTC: The percentage difference in the total cost between the 4CM and SCCM.
- GSC: The percentage difference in the shipper cost between the 4CM and SCCM.
- GCC: The percentage difference in the carrier cost between the 4CM and SCCM.
- A: Fuel cost
- B: Holding cost
- C: Maximum allowance proportion for the difference between the cost of each carrier and the average cost of all carriers
- D: Demand
- E: Number of vehicles per carrier
- MT: Solver stopped at 11 hours
- CPU: Computational
- Gap: The percentage difference between the results obtained from the proposed method and the lower bound.

There are literature reviews on the CTM topic as follows. Verdonck *et al.* [9] proposed an overview of solution techniques to sharing order and capacity for the operational planning of horizontal cooperation between road transportation carriers. Later, Guajardo and Rönnqvist [10] surveyed more than 40 cost allocation methods for collaborative transportation issues. Gansterer and Hartl [11] reviewed optimization models and solution techniques for collaborative transport planning and classified three major streams of research based on collaborative planning for operational decisions. Later, Gansterer and Hartl [12] explore up-to-date literature related to shared resources in collaborative vehicle routing and classify according to the required level of information sharing. Pan *et al.* [13] provide a review of the horizontal collaborative transport solution and implementation issues. In a recent literature review, Aloui *et al.* [14] examined the existing literature on sustainability and collaboration in the freight transport sector at the strategic, tactical and operational levels. Karam *et al.* [15] reviewed and identified 31 different barriers to implementing collaborative transport networks (CTNs). A conceptual barrier framework was developed by grouping the 31 barriers into five categories: the business model, information sharing, human factors, collaborative decision support systems, and the market. In addition, they proposed the stage-gate model integrating the conceptual barrier framework into the collaborative transportation network (CTN) implementation decision-making process. The seven review articles above show that there has been an increase in collaborative transport studies over the past few years, and there are still many gaps and opportunities for future research. In recent years, a large number of collaborative transportation planning studies have been conducted. Wang *et al.* [16] formulated a bi-objective programming model and solved a collaborative multi-depot vehicle routing problem with time window assignment using a hybrid heuristic algorithm to reduce the operating costs and the total number of delivery vehicles. Los *et al.* [17] proposed a multi-agent system to solve collaborative vehicle routing problems and investigate the effectiveness of carrier information for platform-based collaborative vehicle routing. They discovered that sharing cost and route information improves solutions in total route costs and that sharing marginal costs improves service quality. When no costs are shared among carriers, transportation costs are significantly higher. If they do not wish to share their costs every time, even occasional sharing results in a greater improvement. Shi *et al.* [18] proposed a method to solve the collaborative multi-carrier vehicle routing problem to reduce transportation costs and share the profit fairly with individual players. Maneengam and Udomsakdigool [19] proposed a covering model with a screening technique to reduce the initial problem size for collaborative bidirectional multi-period vehicle routing problems under profit-sharing agreements in bulk transportation. Wang *et al.* [20] developed a multi-objective optimization model to formulate the multi-depot multiperiod vehicle routing problem with pickups and deliveries. Moreover, they proposed a hybrid heuristic algorithm to solve the problem and used the minimum cost remaining savings method to allocate the cost for each participant in the collaboration. Padmanabhan *et al.* [21] investigated the possible benefits of collaboration among less than truckload carriers in fulfilling pickup and delivery problem to minimize the total transportation cost. They proposed a mathematical model and a solution method based on the large neighborhood search. Karels *et al*. [22] investigated an auction method to help carriers collaborate while maintaining autonomy for the individual carriers. They found the reassignment auction to be a very viable collaborative environment for carriers, offering significant savings over previously reported methodologies in the literature. Zhang *et al*. [23] proposed a new collaborative vehicle routing model with shared carriers and depots. A composite objective weighted sum of four objectives is used in the proposed model, which employs an extended variable neighborhood search algorithm based on three matrices: the carrier collaboration matrix, depot collaboration matrix, and transportation sequence matrix to solve the problem. Wang *et al.* [24] proposed an integrated modeling method considering the objectives at both the coalition and partner levels for a collaborative multi-center vehicle routing problem. Then, they solved the model using the nondominated sorting genetic algorithm-large neighborhood search. Mancini *et al.* [25] introduced the collaborative consistent vehicle routing problem with time and service consistency and workload balance. They used the mixed integer programming model for small-sized instances and proposed an effective metaheuristic and an iterative local search algorithm for larger instances. Wang *et al.* [26] formulated a multi-objective integer programming model that minimizes costs, service waiting times, and the number of vehicles for a two-echelon collaborative multi-depot multi-period vehicle routing problem. They proposed a hybrid heuristic algorithm with three-dimensional k-means clustering and an improved reference point-based nondominated sorting genetic algorithm-III (IR-NSGA-III) to solve the multi-objective integer programming model. Mrabti *et al.* [27] proposed mixed integer linear programming for the pooling of sustainable freight transport to minimize CO_2 emissions and various logistical costs. They solved the model with the ε-constraint method. Additionally, they compared the performances of the pre-pooling, the economic pooling, and the ecological pooling scenarios. Aloui *et al.* [28] formulated a multi-objective integer programming model for a collaborative and integrated two-echelon inventory, location and routing problem to minimize logistics costs, CO_2 emissions and accident rates and solve the problem using a hybrid heuristic based on machine learning. They found that the total cost, CO_2 emissions, and accident risk were significantly reduced after the collaboration. Aloui *et al.* [29] studied the benefits of collaborative and non-collaborative scenarios by proposing bi-objective mixed-integer linear programming for integrated planning problems of location, inventory, and routing to design two-echelon green logistics networks. Wang *et al.* [30] proposed a hybrid genetic algorithm with tabu search to solve the collaborative multi-depot pickup and delivery vehicle routing problem with split loads and time windows to reduce operating costs through logistics resource sharing. They compared collaborative versus non-collaborative networks and found that collaborative networks resulted in lower transportation costs, increasing the service to more customers, but this took more time to calculate. Zheng *et al.* [31] proposed mixed-integer linear programming for collaborative vehicle routing in the urban ring logistics network under the COVID-19 epidemic and solved the problem using the variable neighborhood search algorithm. They found that the total cost of vehicle and distance before joining the collaboration was greater than that after joining the collaboration. Hacardiaux *et al.* [32] proposed an optimization framework that considers each partner's interests. All partners can identify their needs considering reduced transport costs versus reduced CO_2 emissions. For this reason, all stakeholders are likely to agree with this solution, and long-term interoperability is improved. Vahedi-Nouri *et al.* [33] developed two bi-objective mathematical models for a capacitated electric vehicle routing problem under collaborative and non-collaborative strategies and solved the problem using a metaheuristic approach based on the integration of the multi-objective Keshtel algorithm (MOKA) with a mathematical model. Additionally, they found that a collaborative strategy can lower total costs and electrical energy consumption, as well as considerably improve customer service levels and vehicle utilization. Yang and Wang [34] developed an adaptive genetic algorithm combined with a scanning algorithm to solve the network collaborative distribution model based on vehicle sharing. They found that vehicle sharing can effectively improve the efficiency of the distribution network and reduce costs. Wang *et al.* [35] formulated a mixed-integer programming model to minimize logistics operating costs using a two-stage hybrid algorithm combining an improved 3D k-means clustering algorithm and the genetic algorithm and particle swarm optimization algorithm to solve the collaborative multicenter vehicle routing problem with time windows and mixed deliveries and pickups. Furthermore, the minimum costs-remaining savings model was applied to design a fair and reasonable profit allocation plan for participants in the collaborative alliance and partnership stabilization. A comparative overview of the existing research studies in the field of collaborative vehicle routing problems between 2020 and 2022 and the current paper is presented in Table 1.

In Table 1, we list all publications falling into the category of collaborative vehicle routing problem. The following criteria were used to further categorize the studies:

- Type of performance indicators: the total operating cost or the total profit (P1), travel costs (P2), holding cost or storage cost (P3), reliability (P4), quality (P5), waiting

TABLE 1. References in the collaborative vehicle routing problem field.

Reference	Key Performance indicators												Strategy studied			IFT	SOC
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	NC	CO	4C		
Wang *et al.* [16]	✓	-	-	-	-	-	-	✓	-	-	-	-	✓	✓	-	-	-
Los *et al.* [17]	✓	✓	-	-	-	-	✓	-	-	-	-	-	✓	✓	-	-	-
Shi *et al.* [18]	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
Maneengam and Udomsakdigool [19]	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
Wang *et al.* [20]	✓	-	-	-	-	✓	-	✓	-	-	-	-	✓	✓	-	-	-
Padmanabhan *et al.* [21]	-	✓	-	-	-	-	-	-	-	-	-	-	✓	✓	-	✓	-
Karels *et al.* [22]	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-
Zhang *et al.* [23]	✓	-	-	✓	✓	✓	-	-	-	-	-	-	-	✓	-	-	-
Wang *et al.* [24]	✓	-	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-	-
Mancini *et al.* [25]	-	-	-	-	-	✓	✓	-	-	-	-	-	✓	✓	-	-	-
Wang *et al.* [26]	✓	-	-	-	-	✓	-	✓	-	-	-	-	✓	✓	-	-	-
Mrabti *et al.* [27]	✓	✓	✓	-	-	-	-	-	✓	✓	-	-	✓	✓	-	-	-
Aloui *et al.* [28]	✓	-	-	-	-	-	-	-	✓	✓	-	-	✓	✓	-	-	-
Aloui *et al.* [29]	✓	✓	✓	-	-	-	-	-	✓	-	-	-	✓	✓	-	✓	-
Wang *et al.* [30]	✓	-	-	-	-	-	-	✓	-	-	-	-	✓	✓	-	-	-
Zheng *et al.* [31]	✓	✓	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-
Hacardiaux *et al.* [32]	✓	-	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-	-
Vahedi-Nouri *et al.* [33]	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	✓	-	✓	-
Yang and Wang [34]	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
Wang *et al.*[35]	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-
The current paper	✓	-	-	-	-	-	-	-	-	-	✓	✓	-	✓	✓	✓	✓

time or transportation time (P6), service level (P7), number of vehicles (P8), CO_2 emissions (P9), accident rate or noise level (P10), shipper cost (P11), and carrier cost (P12).

- Type of strategy studied: non-collaboration (NC), collaboration for a single supply chain (CO) or a cross-chain collaboration center (4C).
- Is investigating the effect of critical factors on transportation performance (IFT) considered?: Yes or No.
- Is studying opportunities and providing decision-making tools to implement a cross-chain collaboration for each possible situation (SOC) considered?: Yes or No.

Our review revealed that most researchers have focused on total cost and profit to evaluate performance because this indicator is significant to the logistics business. Only the study by Mancini *et al.* [25] used performance indicators for waiting time and service level without considering any cost-related indicators. More considerations of other performance indicators have been added, including environmental, social impact, quality, and storage costs. A study that examined and compared collaboration with non-collaboration settings showed that CTM provides superior performance and cost benefits when compared to non-collaborative solutions [3], [4], [11], [16], [17], [20]–[22], [25]–[31], [33], [35], [37], [36]–[39]. Although we know that the 4C model (4CM) can lower the total cost, it can possibly increase the cost for some parties, and change is almost impossible if there reËmains a barrier due to human factors. Many involved parties are unaware of 4CM benefits and may fear changing their business model [15]. The reasons above pose significant obstacles for many parties; thus, they are reluctant to join collaborative networks. We found that no existing studies have comprehensively examined the impact on all concerned parties. In addition, there is on research that studies the probability of changing from an SCCM to a 4CM in each possible situation based on the perspectives of actual network participants (shippers and carriers) under uncertain circumstances.

In this paper, we investigated the impact of the 4CM on transportation performance, including the percentage differences in the total cost, shipper cost and carrier cost, using a central composite design (CCD) for five independent parameters that, include the fuel cost (A), holding cost (B), maximum allowance proportion for the difference between the cost of each carrier and the average cost of all carriers (C), demand (D) and number of vehicles per carrier (E). These uncertain parameters depend on the world economic situation, and we used the data from 2009-2021 to define the respective levels of each factor (low level, center point, high level). An integer linear programming (ILP) method based on route representation was used to solve the collaborative bidirectional multi-period vehicle routing (CBMVRP) and evaluate the benefits of the proposed 4CM in the context of bulk transportation in Thailand. Moreover, we organized a focus group to collect data about the criteria and the probability of changing from the SCCM to the 4CM in the case study network and then generated a classification tree of the levels of possibility to change from the SCCM to the 4CM for the current network situation using the ID3 algorithm based on the data set obtained from the focus group. This is the first paper to examine the impact of 4C in each possible situation on transport performance and provide a classification tree to assess opportunities to implement a cross-chain collaboration.

The remaining sections of this paper are organized as follows. In Section II, the problem in a collaborative bulk transportation network is described, and two collaborative models, the SCCM and 4CM, are proposed. The methodology used to determine the impact of the 4CM is presented in Section III. A case study is presented in Section IV. The results and discussion are presented in Section V. Finally, the conclusions are given in Section VI.

II. PROBLEM DESCRIPTION

The organizations in a transportation chain ($\tau \in \Omega$) include customers, shippers and many carriers ($k_\tau \in K_\tau$). This paper assumed that carriers own and operate transportation equipment, while shippers own or supply the shipment and accept the work from customers. We set the collaborative bulk transportation network (CTN) as the allied organizations together with those collectively using a transportation plan to make centralized decisions, and all carriers can perform transportation operations for all jobs of one or many shippers in the CTN under the same cost-sharing agreement. Therefore, the CTN consists of members in one transportation chain or multiple transportation chains, depending on the collaborative model chosen. In this paper, the CBMVRP determines the transport routes for each carrier, and all jobs are efficiently allocated to the carrier in the CTN. The objective is to minimize the total cost while ensuring that all deliveries are made to fit the various time window constraints, demand constraints, capacity constraints for terminals and carriers and cost-sharing allocation constraints. When bulk cargo is transported using trucks, the scenario is termed the full truckload transport problem, whereby the carriers must transport the cargo between specific terminals under non-consolidation conditions. In this type of bulk transportation network, the terminal can be either the origin or the destination. The time window constraints in this problem are given as follows. In the first constraint, the customer sets the time window for the job, and if the delivery takes place after the due date, the carrier will be fined in accordance with the contract terms. In the second constraint, the work periods of drivers must be in accordance with the legal limits regarding driving hours. It must be noted that terminal 0_k serves as the depot of carrier k. In this case, all companies involved will specify the maximum acceptable proportion of the differences between the cost for each carrier and the average cost for all carriers (c) of each network in their contract before solving the problem by a selected parameter value $c \in [0, 1]$ to use in the cost-sharing allocation constraints. A list of associated assumptions is as follows.

- Every vehicle from every carrier must depart from the origin depot at the start of every working period and must return to the depot of carrier k prior to the end of the period.
- Every carrier has only one depot of origin.
- Each carrier has a fleet of vehicles with limited capacity at the depot of carrier k to perform the jobs.
- Each terminal has a working time of one period.
- All carriers use the same type of truck and each truck must carry the same weight.
- All periods are of the same duration.
- Cargo splitting and delivery are permissible, so a vehicle is able to pick up and deliver the same product a number of times to meet customer demands.
- All carriers can accept external jobs (outside the pool) on their own during their free time, but this must not affect their network assignments. The paper did not consider external jobs of each carrier.

The notation of the model for the CTN is given in Table 2.

A. SINGLE-CHAIN COLLABORATION MODEL FOR BIDIRECTIONAL MULTI-PERIOD VEHICLE ROUTING (SCCM)

The various carriers in transportation chain τ (the sets of transportation chain τ and CTN i are the same) are always willing to share cost information, even if this does not improve the local vehicle profit. All involved parties in the transportation chain τ share shipment order, transportation cost data, holding cost data, customer demand, and vehicle capacity of each carrier. The shipper is responsible for routing and sharing their complete route plans with all carriers in transportation chain τ. Shipper and carriers collaborate only within a transportation chain, and there is no collaboration between transportation chains. In the SCCM setting, each participant in transportation networks i, i ∈ (1…, I), minimizes the total cost of transportation chain i (TC_i). Therefore, the total cost of multiple transportation chains in the SCCM (TC^{SCCM}) is the summation of the total cost of CTN i, as shown in (1). The SC^{SCCM} and the CC^{SCCM} are the total shipper cost and total carrier cost of multiple transportation chains, respectively, as shown in (2) and (3). The management cost of each CTN using the SCCM (μ^{SCCM})) consists of expenses for hiring staff to plan and control transportation and rental prices for solvers and programs, and these costs are fixed.

$$TC^{SCCM} = \sum_{i \in I} TC_i = \sum_{i \in I} SC_i + \sum_{i \in I} CC_i \tag{1}$$

$$SC^{SCCM} = \sum_{i \in I} SC_i \tag{2}$$

$$CC^{SCCM} = \sum_{i \in I} CC_i \tag{3}$$

We provided an example of two independent transportation chains using the SCCM setting, as illustrated in Fig. 1 and Fig. 2. Each transportation chain includes one customer, one shipper, and two carriers. There are 10 jobs in total. Job number 1-5 belongs to customer 1, and number 6-10 belongs to customer 2. Fig. 1 shows that CTN 1 includes collaboration among parties in transportation chain 1 only without cross-chain collaboration, as does CTN 2. In CTN 1, the customer

TABLE 2. List of notations.

Symbol	Description
Sets	
I	Set of collaborative bulk transportation network, $i \in I$
J_i	Set of jobs in CTN i. $j_i \in J_i$
J_τ	Set of jobs in transportation chain τ. $j_\tau \in J_\tau$
K_i	Set of carriers in CTN i. $k_i \in K_i$
K_τ	Set of carriers in transportation chain τ. $k_\tau \in K_\tau$
P	Set of terminals. $p \in P$
R_{k_i}	Set of feasible routes of carrier k in CTN i. $r_{k_i} \in R_{k_i}$
T	Set of periods. $t \in T$
Ω	Set of the transportation chain. $\tau \in \Omega$
Parameters	
$\gamma_{j_i r_{k_i}}$	A binary parameter that takes a value of 1 if route r_{k_i} must transport job j_i and 0 otherwise.
$\eta_{p r_{k_i}}$	The frequency of using terminal p in route r_{k_i} (Trips)
λ_{j_i}	Penalty for the late delivery of job j_i (Baht)
μ^{4cm}	Total management and collaboration cost when using 4CM (Baht)
μ^{SCCM}	Management and collaboration cost in CTN i when using SCCM (Baht)
φ^{4CM}	A binary parameter that takes a value of 1 if CTN i using 4CM and 0 otherwise.
φ^{SCCM}	A binary parameter that takes a value of 1 if CTN i using SCCM and 0 otherwise.
θ	The coordinated decision-making cost (Baht)
ϑ	The cost of transportation control per trip (Baht/trip)
a	Fuel cost per liter (Baht/liter)
b_{j_i}	Holding cost of job j_i (Baht/trip/period)
c	The maximum acceptable proportion of the differences between the cost of each carrier and the average cost of all carriers, $c \in [0,1]$
$c_{r_{k_i} t}$	Cost of carrier k_i for route r_{k_i} in period t (Baht/vehicle)
d_{j_i}	Demand of job j_i (Trips)
e_{j_i}	Earliest allowed arrival time of job j_i (Date)
g_{pt}	The ability to accommodate trucks from terminal p (Trips)
$f_{r_{k_i}}$	Fuel used for route r_{k_i} by a vehicle of carrier k in CTN i (Liter/vehicle)
$h_{j_i t}$	Holding cost of job j_i in period t (Baht/trip)
l_{j_i}	Latest allowed arrival time of job j_i (Date)
m	A large positive number
$n_{j_i r_{k_i}}$	The frequency of job j_i for route r_{k_i} (Trips)
q	Drivers' working hours for one period (Hours)
u_{k_i}	The number of vehicles available of carrier k_i (Vehicles)
Variables	
$\bar{C}$	Average cost of all carriers (Baht)
CC_i	The carrier cost of CTN i (Baht)
SC_i	The shipper cost of CTN i (Baht)
TC_i	The total cost of CTN i (Baht)
TC^{SCCM}	Total cost of single-chain collaboration model (Baht)
SC^{SCCM}	Shipper cost of single-chain collaboration model (Baht)
CC^{SCCM}	Carrier cost of single-chain collaboration model (Baht)
TC^{4CM}	Total cost of cross-chain collaboration center model (Baht)
SC^{4CM}	Shipper cost of cross-chain collaboration center model (Baht)
CC^{4CM}	Carrier cost of cross-chain collaboration center model (Baht)
Decision variable	
$X_{r_{k_i} t}$	The number of vehicles of carrier k_i used in route r_{k_i} at period t (Vehicles)

assigns job 1-5 to shipper 1, and then all carriers in CTN i fully share cost information and vehicle capacity with shipper 1. Then, shipper 1 shares their complete route plans with all carriers in CTN i. Fig. 2 shows that carriers 1 and 2 of shipper 1 have to transport any job in CTN 1 only (job number 1-5), and they are unable to transport in CTN2 (job number 6-10). In addition, CTN 2 has the same management model as CTN 1. For example, carrier 1 of shipper 1 is assigned to travel from their depot to pick up and deliver job 1, and job 2 returns to the depot.

B. CROSS-CHAIN COLLABORATION CENTER MODEL OF BIDIRECTIONAL MULTI-PERIOD VEHICLE ROUTING (4CM)

In this paper, we proposed a 4CM to create a cross-collaborative approach in multiple transportation chains. This model uses the independent control tower to provide centralized collaborative decision making for various shippers and carriers in multiple transportation chains, and costs are shared equitably among the various carriers. In addition, the 4CM includes a pool of information, decision making, freight jobs and transportation resources provided by many shippers and carriers in all CTNs. As a result, all parties involved can use the resources and perform jobs in other transportation chains. Equation (4) describes the relationship between the number of jobs in transportation chain t and the number of jobs in the CTN when shippers share jobs in the CTN. The relationship between the number of carriers in transportation chain τ and the of carriers in the CTN when shippers and carriers share transportation resources in the CTN is shown in (5). J_τ is the set of jobs in transportation chain τ, and J_i is the set of jobs in CTN i ($j_\tau \in J_\tau$, $j_i \in J_i$, $J_\tau \subset J_i$). All shippers have management costs when using 4CM (μ^{4CM}) that must be paid to the control tower; these costs consist of the coordinated decision-making cost (θ) and the cost of transportation control, as shown in (6).

$$J_i = \sum_{\tau \in \Omega} J_\tau \tag{4}$$

$$K_i = \sum_{\tau \in \Omega} K_\tau \tag{5}$$

$$\mu^{4cm} = \theta + \vartheta \left(\sum_{j_i \in J_i} d_{ji} \right) \tag{6}$$

All shippers and carriers share all relevant information (shipment order, demand of each job, transportation cost data, holding cost data, capacity of each carrier) on the website (database) of the transportation control tower. The control tower uses the information obtained from the database for transportation planning. Subsequently, the transportation control tower uploads the transport plan (route for each carrier, the number of trucks for route r at period t) to the website. All involved parties must receive an email informing them about the transportation plan to access the information and transportation plans quickly and accurately. The 4CM

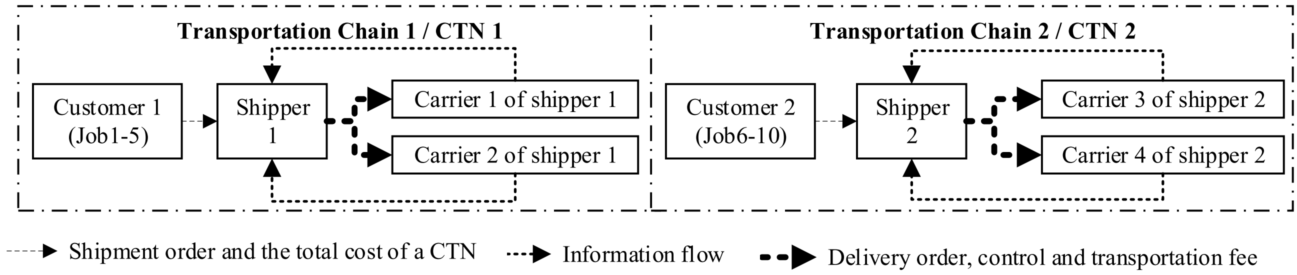

FIGURE 1. **Example of a single-chain collaboration model.**

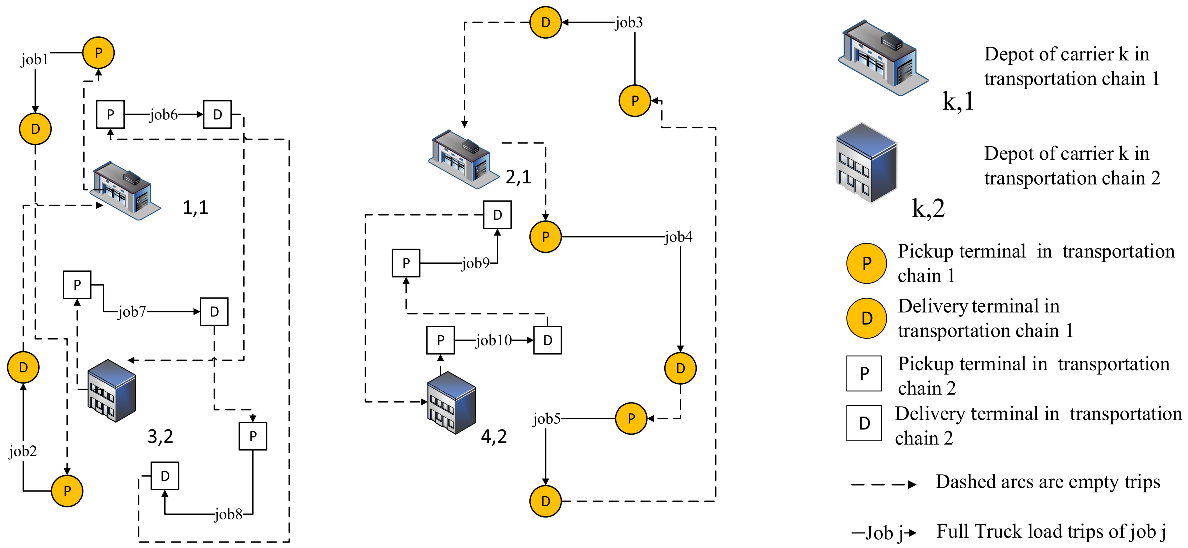

FIGURE 2. **Example of single-chain collaboration vehicle routes of 4 carriers with pickup and delivery requests.**

extends from the basic structure of the collaborative decision support system of Karam *et al.* [15] by increasing the consideration of shippers in the network and having multiple transportation chains in the CTN. In this way, the information relating to the cost and capacity of each individual carrier and shipper is not revealed to other parties. Moreover, it can be assumed that the transportation control tower will act in a fair manner to all parties because the control tower has no conflicts of interest or stakes in freight operation [5]. For the above reasons, each transportation chain is combined into one CTN (I is always equal to 1). The objective of the model is to reduce the total cost of multiple transportation chains ($TC^{4CM} = TC_i$)), including the shipper cost ($\mathrm{SC}^{4\mathrm{CM}} = \mathrm{SC}_i$)) and carrier cost ($\mathrm{CC}^{4\mathrm{CM}} = \mathrm{CC}_i$). We used the same example as in the SCCM to explain the details of the 4CM, as shown in Fig. 3 and Fig. 4. Fig. 3 shows that the CTN includes collaboration among parties in transportation chains 1 and 2 with cross-chain collaboration. Fig. 4 shows that customers 1 and 2 can assign any job to shippers 1 and 2. Then, all participants in the CTN fully share information with the control tower, and the control tower shares their complete route plans with all participants in the CTN. Fig. 4 shows that carriers 1 and 2 of shipper 1 can transport all jobs (job number 1 - 10) in the CTN as well as carriers 3 and 4 of shipper 1. The comparison between Fig. 2 and Fig. 4 shows that when using the 4CM, trucks can travel to pick up and deliver goods across the transport chain, reducing the total distance compared to the SCCM. On the other hand, when using SCCMs, trucks must travel long distances to pick up and deliver goods in the same transportation chain (τ). For example, in Fig. 2, carrier 2 in τ 1 is assigned to transport the job orders 3, 4, and 5, which involves a very long distance because carrier 1 in τ 1 is too far away and carrier 4 in τ 2 cannot transport to these locations, even if their depot is closer than carrier 2 in τ 1. In Fig. 4, all carriers can pick up and deliver at a location near their own depot without transportation chain conditions. This allows decision-makers to better reduce the total distance by allowing shippers to transport cargo close to their own depot. By cross-collaboration, decision-makers can reduce empty return trip distances because this model allows carriers to transport cargo close to their own depot.

C. MODEL FORMULATION

In this paper, we presented an integer liner programming model to explain the CBMVRP in one CTN; this integer liner programming model aimed to find the number of vehicles required for route r of carrier k_i from all feasible routes

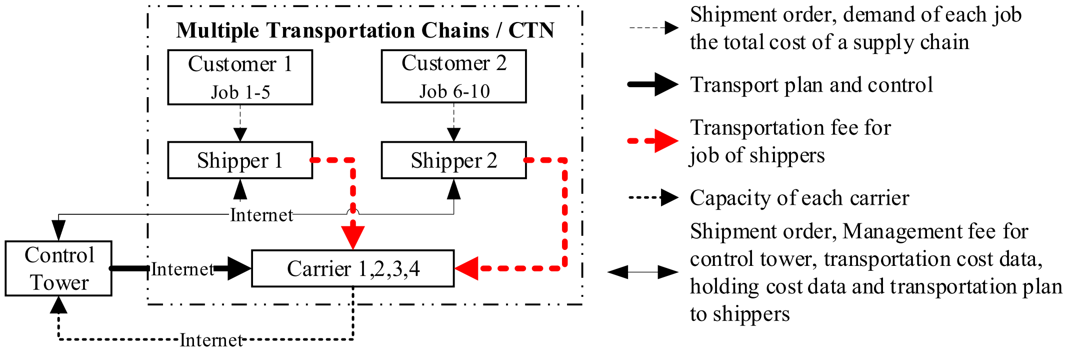

FIGURE 3. Cross-chain collaboration center model for the CTN.

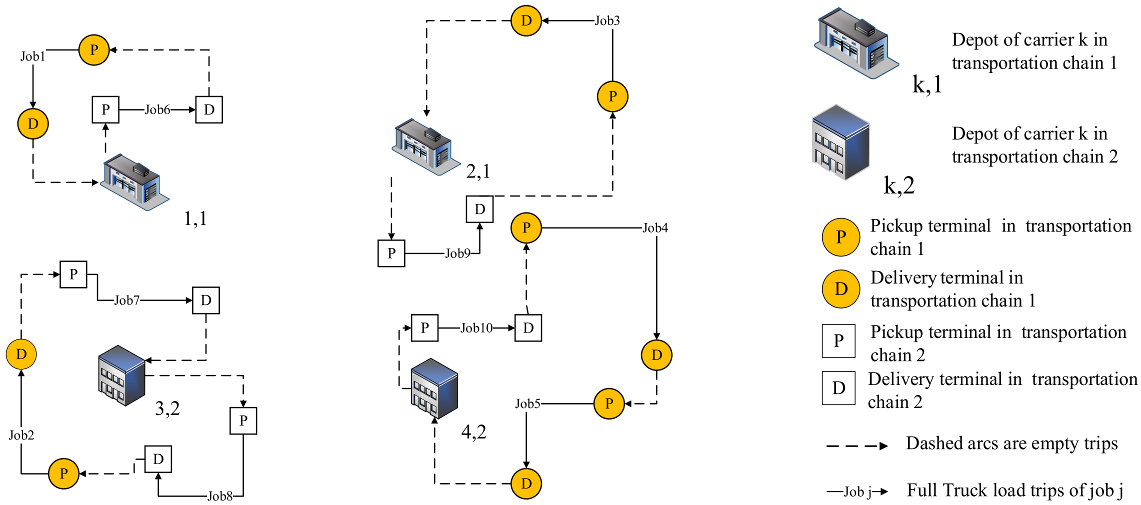

FIGURE 4. Example of cross-chain collaboration center vehicle routes of 4 carriers with pickup and delivery requests.

in set R_{ki} in each period t for the CBMVRP based on the model formulation of Maneengam and Udomsakdigool [19]. This integer liner programming model can be used to solve the problems for both collaboration models, and the two collaboration models differ based on the total cost of multiple transportation chains and management costs. The objective function minimizes the total cost in CTN i, which consists of the shipper cost (SC_i) and the carrier cost (CC_i) in CTN i, as shown in (7). To implement this model formulation, the carriers require the maximum acceptable proportion of the differences between the cost of each carrier and the average cost of all carriers (c) within a predetermined threshold determined by a selected parameter value $c \in [0, 1]$. This model formulation is based on a standard ε constraint method [40] to reduce the bi-objective optimization problem to a single-objective optimization problem [41]. Recall that $c = 1$ indicates that the carriers can receive costs of up to 100% of the average cost, and the opposite is true when $c = 0$, meaning that carriers can receive costs equal to the average cost. Thus, the cost of carrier k is close to that of other carriers, as agreed upon in the contract. The model formulation of CTN i can be described as follows.

$$\textit{Minimize} \quad TC_i = SC_i + CC_i \tag{7}$$

subject to

$$\sum_{k_i\in K_i}\sum_{r_{k_i}\in R_{k_i}}\left[\left(\sum_{t\in T} x_{r_{k_i}t}\right) n_{j_i r_{k_i}}\gamma_{j_i r_{k_i}}\right] \geq d_{j_i},\ \forall j_i \in J_i. \tag{8}$$

$$\sum_{k_i\in K_i}\sum_{r_{k_i}\in R_{k_i}} X_{r_{k_i}t} \leq u_{k_i},\ \forall t \in T. \tag{9}$$

$$\sum_{k_i\in K_i}\sum_{r_{k_i}\in R_{k_i}} X_{r_{k_i}t}\eta_{pr_{k_i}} \leq g_{pt},\ \forall p \in P,\ \forall t \in T. \tag{10}$$

$$\sum_{r_{k_i}\in R_{k_i}}\sum_{t\in T} X_{r_{k_i}t}c_{r_{k_i}t} - \left[\bar{C} - \left(c \times \bar{C}\right)\right] \geq 0,\ \forall k_i \in K_i. \tag{11}$$

$$\left[\bar{C} - \left(c \times \bar{C}\right)\right] - \sum_{r_{k_i}\in R_{k_i}}\sum_{t\in T} X_{r_{k_i}t}c_{r_{k_i}t} \geq 0,\ \forall k_i \in K_i. \tag{12}$$

$$X_{r_{k_i}t} \in \text{int},\ \forall k_i \in K_i,\ \forall r_{k_it} \in R_{k_it},\ \forall t \in T. \tag{13}$$

where

$$SC_i = \left[\sum_{j_i\in J_i}\sum_{t\in T}\sum_{r_{k_i}\in R_{k_i}}\sum_{k_i\in K_i} X_{r_{k_i}t}n_{j_i r_{k_i}}h_{j_it}\right] + \left[\mu^{4CM}\varphi^{4CM}\right] + \left[\mu_i^{SCCM}\varphi_i^{SCCM}\right] \tag{14}$$

$$CC_i = \sum_{k_i\in K_i}\sum_{r_{k_i}\in R_{k_i}}\sum_{t\in T} X_{r_{k_i}t}c_{r_{k_i}t} \tag{15}$$

$$c_{r_{k_i}t} = \begin{cases} a\left(f_{r_{k_i}}\right), \max_{j_i \in J_i}\left(e_{j_i}\gamma_{j_i r_{k_i}}\right) \le t \le \min_{j_i \in J_i}\left(l_{j_i}\gamma_{j_i r_{k_i}}\right) \\ a\left(f_{r_{k_i}}\right) + \left[\sum_{j_i \in J_i}\left(t - l_{j_i}\right)\lambda_{j_i}\gamma_{j_i r_{k_i}}\right], t > l_{j_i} \\ m, \text{ otherwise} \end{cases} \quad (16)$$

$$h_{j_i t} = \begin{cases} b_{j_i}\left(t - e_{j_i}\right), \ e_{j_i} \le t \\ m, \text{ Otherwise} \end{cases} \quad (17)$$

$$\bar{C} = \frac{\sum_{r_{k_i} \in R_{k_i}} \sum_{k_i \in K_i} \sum_{t \in T} X_{r_{k_i}t} c_{r_{k_i}t}}{K_i} \quad (18)$$

Constraint (8) ensures that the transportation plan is able to transfer goods completely according to the requirements of job j in CTNi. Constraint (9) ensures that the number of vehicles used during period t does not exceed the number of vehicles that carrier k_i can provide in that period. Constraint (10) ensures that the total frequency specified at terminal p being used in a given period t does not exceed the capacity of terminal p for loading and unloading. Constraint (11) ensures that the cost of each carrier is greater than the minimum cost specified in the contract. Constraint (12) ensures that the cost of each carrier is less than the maximum cost specified in the contract. Equation (13) ensures that the decision variables are nonnegative integer values. Equation (14) describes the shipper cost in CTNi, and (15) describes the carrier cost in CTNi. Equation (16) gives the cost components when route r is used during the allowable transportation time; these components consist of the cost and a penalty when the completion date is later than the time specified in the contract. Equation (17) describes the components of the holding cost. If period t is greater than e_i, the holding cost increases as the holding time increases. Otherwise, the cost is used to specify m. Equation (18) is the average profit of each carrier.

III. METHODOLOGY

In this paper, the research methodology used to determine the impact of the 4CM is shown in Fig. 5. Fig. 5 shows 6 main steps, including the experimental design, solution of the CBMVRP in the CTN with both the 4CM and SCCM, calculation of the response data and statistical analysis.

A. DESIGN OF THE EXPERIMENTS

A CCD was used to create design experiments with one center point and five uncertain input parameters set at low and high levels: the fuel cost (A), holding cost (B), maximum acceptable proportion of the differences between the cost of each carrier and the average cost of all carriers (C), demand (D) and the number of vehicles (E). We defined the axial points at the center of each face of the factorial space (face cantered design). The design matrix and the response data were obtained from a single replicate of 43 factorial experiments using Minitab 19 software. The values of each parameter and their respective levels are presented in Table 3.

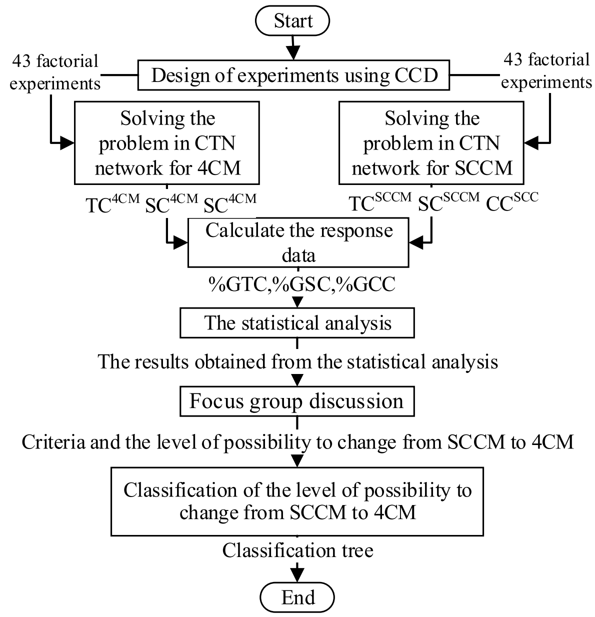

FIGURE 5. A flow chart of the research methodology.

TABLE 3. Uncertain input parameters and their levels for a comparison between the 4CM and SCCM.

Uncertain input parameters	Parameter in model formulation	Symbol	Low level	Center point	High level
Fuel cost (Baht/liter)	a	A	11.1	20.55	30
Holding cost (Baht/trip/period)	b_{j_i}	B	25	137.5	250
Maximum acceptable proportion of the differences between cost of carrier k and average cost of all carriers	c	C	0.1	0.55	1
Demand per job (Trips)	d_{j_i}	D	80	125	170
The number of vehicles available per carrier (Trucks)	u_{k_i}	E	5	20	35

B. THE METHOD TO SOLVE THE CBMVRP WITH BOTH THE 4CM AND SCCM

In this section, we present a method to solve the CBMVRP based on a route representation, as shown in Fig. 6.

The details of the flow chart of the method to solve the CBMVRP are as follows:

Step 1: All feasible routes are first generated to solve the CBMVRP. All feasible routes for each carrier in CNT i are generated in this step, and the parameters are defined, including $n_{j_i r_{k_i}}$, $\eta_{p r_{k_i}}$, $\gamma_{j_i r_{k_i}}$ and $f_{r_{k_i}}$, to use in the integer linear programming (ILP) model. A feasible route is a vehicle travel sequence from the depot to other terminals and returning to the same depot in less than one period or eight working hours on one day. We defined v and w as indices of the departure and arrival operation sequence numbers on route r_{ki}, respectively (v, w $\in V_{rki}$). Each operation sequence number v involves a pick-up terminal (a_v) and a destination

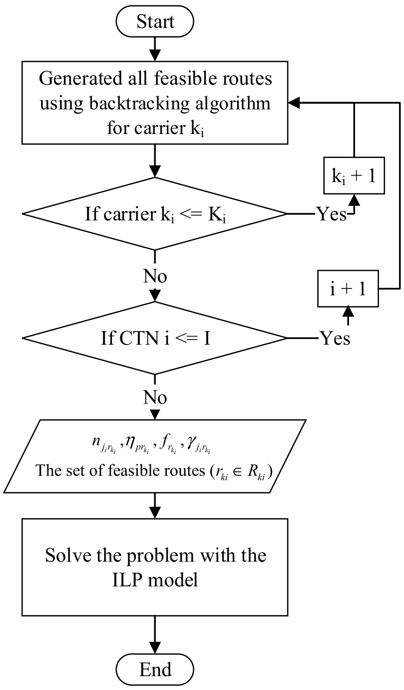

FIGURE 6. The flow chart of the method to solve the CBMVRP.

terminal (b_v): (a_v, b_v $\in$ P). Note that the depot of carrier k is terminal 0_{ki} ($v = 0$). An example of the generation of a feasible route for a vehicle of carrier k in CNT i is shown in Fig. 7.

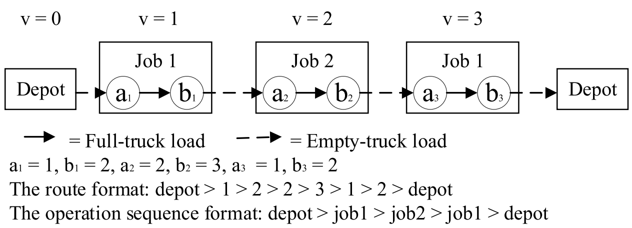

FIGURE 7. Example of the generation of a feasible route for a vehicle of carrier k in CNT i.

In Fig. 7, the following is a description of a possible truck route. The vehicle leaves the depot and then performs job 1 by loading at terminal 1 and discharging at terminal 2. The truck subsequently completes job 2 by loading the product at terminal 2 and discharging it at terminal 3. Finally, the truck returns to the depot after completing job 1 by loading the product at terminal 1 and discharging it at terminal 2. This route sequence can be written in route format as {depot>1>2>2>3>1>2>depot}, and it can be written in operation sequence format as {depot>job1>job2>job1> depot}. We define the fuel cost (f_{vw}) and the travel time (S_{vw}) from operation sequence v to w. After obtaining route r_k, we defined the loading terminal (a_v) and unloading terminal (b_v) of operation sequence v to calculate t_{vw} and $c_{vw,}$ as shown in Equations (19) and (20).

$$s_{vw} = \begin{cases} s_{0_{k_i}a_v}, & v = 0 \\ s_{a_v} + s_{a_v b_v} + s_{b_v} + s_{b_v 0_{k_i}}, & v = V_{r_{k_i}} \\ s_{a_v} + s_{a_v b_v} + s_{b_v} + s_{b_v a_w}, & otherwise \end{cases} \tag{19}$$

$$f_{vw} = \begin{cases} f_{0_{k_i}a_v}, & v = 0 \\ f_{a_v b_v} + f_{b_v 0_{k_i}}, & v = V_{r_{k_i}} \\ f_{a_v b_v} + f_{b_v a_w}, & otherwise \end{cases} \tag{20}$$

The backtracking algorithm of Maneengam and Udomsakdigool [42] was applied to enumerate a set of feasible routes of carrier k in CTN i that satisfy the constraint of drivers' working hours for one period to give all the feasible routes of carrier k in CTN i, as shown in Equation (21).

$$\sum_{v \in V_{r_{k_i}}} \sum_{w \in V_{r_{k_i}}} s_{vw} \leq q, \quad \forall r_{k_i} \in R_{k_i},\ k_i \in K_i,\ i \in I. \tag{21}$$

This algorithm traverses this search tree recursively, from the root down, in depth-first order, and it can guarantee finding all feasible solutions [43]. In this paper, we define the job of CNT i as a node in the search tree of the algorithm. Therefore, when adding a node (job j_i) to create a new subtree in the search tree of the algorithm, it checks whether the total time of route r_{ki} satisfies the constraint and whether the set of feasible routes steps is enumerated as with a general backtracking algorithm. Once the algorithm has successfully enumerated all feasible routes, then all feasible routes can be kept, and the set of routes (r_{ki} $\in$ R_{ki}) indexed. After that, the parameters $n_{j_i r_{k_i}}$, $\eta_{pr_{k_i}}$, $\gamma_{j_i r_{k_i}}$, f_{vw}, s_{vw} are defined from that feasible route (r_{ki}). The fuel cost of route r_{ki} $\left(f_{r_{k_i}}\right)$ is determined by calculating the sum of fuel cost from operation sequence v to w for route r_{ki} (f_{vw}), as shown in Equation (22).

$$f_{r_{k_i}} = \sum_{v \in V_{r_{k_i}}} \sum_{w \in V_{r_{k_i}}} f_{vw} \tag{22}$$

Step 2: If carrier k_i <= K_i, k_i+ 1 and using Step 1 for carrier k_i+ 1 in CTN i, go to the next step.

Step 3: If i <= I, i + 1, return to Step 1. Otherwise, go to the next step. Upon obtaining the solution vector for all carriers, all feasible routes are indexed as the set of routes for carrier k in CTN i (R_{k_i}, $r_{k_i} \in R_{k_i}$, $R_{k_i} \subset R_{K_i}$).

Steps 1-3 create all feasible routes for each carrier in CTN i to separate routing from the number of vehicles required for route r of carrier k_i.

Step 4: Having constructed the set of all feasible routes for all carriers and CTN i, the optimization software (OpenSolver 2.9.4) based on the branch and cut algorithm [44] is used to find the number of vehicles required for route r of carrier k_i from all feasible routes in set R_{ki} in each period t for the CBMVRP with the ILP model. Therefore, this method provides an exact solution. Steps 1, 2, 3 and 4 are applied to both the 4CM and SCCM. In addition, we established the following criteria for terminating the algorithm: integer tolerance of 0.00001 or the maximum computational time limit of 39,600 seconds (11 hours). When the algorithm stopped before the optimal solution was found, we recorded the near-optimal solution instead of the optimal solution.

Step 5: With each model, calculate the total cost (TC^{SCCM}, TC^{4CM}), shipper cost (SC^{SCCM}, SC^{4CM}) and carrier cost (CC^{SCCM}, CC^{4CM}).

C. OBTAINING THE RESPONSE DATA

In this section, we used the results obtained from the method to solve the CBMVRP with both the 4CM and SCCM (TC^{SCCM}, TC^{4CM}, SC^{SCCM}, SC^{4CM}, CC^{SCCM} and CC^{4CM}) to calculate the response data, as shown in (23)-(25). The variable GTC is defined as the percentage difference in the total cost between the 4CM and SCCM. Additionally, GSC is the difference in the shipper cost between the 4CM and SCCM, and GCC is the difference in the carrier cost between the 4CM and SCCM. Recall that a response value > 0 suggests that the 4CM outperforms the SCCM for that response variable. Otherwise, the SCCM performs better than the 4CM.

$$GTC = \left[\left(TC^{SCCM} - TC^{4CM}\right)\Big/ TC^{SCCM}\right] 100\% \quad (23)$$

$$GSC = \left[\left(SC^{SCCM} - SC^{4CM}\right)\Big/ SC^{SCCM}\right] 100\% \quad (24)$$

$$GCC = \left[\left(CC^{SCCM} - CC^{4CM}\right)\Big/ CC^{SCCM}\right] 100\% \quad (25)$$

D. STATISTICAL ANALYSIS

The statistical software Minitab 19 was used to determine the effects and fit of all response variables in the full quadratic model. Then, we considered only the significant effects (with reduced models) on each response variable to determine the impact of the 4CM when compared with that of the SCCM [45].

E. FOCUS GROUP DISCUSSION

The objective of this subsection was to collect information about the criteria and probability of changing from the SCCM to the 4CM of the case study network because many companies are concerned that the transition to the 4CM may not be worthwhile. Therefore, this study was conducted as an online focus group to collect qualitative data from discussions among decision makers from companies involved in the transport network through an online meeting platform. A focus group discussion is a method that allows participants to discuss their ideas and experiences [46]. This method allows for interactive discussions to formulate conclusions or guidelines on the intended objectives; it can collect information to obtain quality, in-depth answers and has a low operation cost compared to other methods [47], [48]. The above merits of online focus group discussions indicate that this method is well-suited to case studies because there is generally very little time to collect information. It is also essential to maintain a distance through an online meeting platform to prevent the spread of coronavirus disease 2019 (COVID-19). The steps for this discussion are as follows:

Step 1: Formulate questions in a semi-structured form that flexibly cover the topic:

- Question 1 (Exploration questions): What is your opinion of the 4CM after learning about its meaning and effects?
- Question 2 (Exploration questions): What criteria do you apply when deciding to switch from the SCCM to the 4CM?
- Question 3 (Exploration questions): Please specify the level of probability of your changing from an SCCM to a 4CM.
- Question 4 (Exit question): Would anyone like to propose other issues or anything else?

Step 2: Nominate 1–2 key individuals per company in the case study network to participate in the focus group discussion. Participants must have the necessary experience or information and be able to make decisions about changing in their planning.

Step 3: Contact the selected people with the focus group times and confirm interest and availability by email. All participants must receive information about their involvement and informed consent to participate. Later, remind them 2 days before the scheduled group.

Step 4: Conduct the focus group using an online meeting platform. First, the moderator explains the purpose and the meaning of the group and describes the impact of the 4CM (the results obtained from the statistical analysis) for the participants to understand. After that, the moderator asks the questions in Step 2. For questions 2–3, the moderator must ask participants to summarize their answers to obtain a single response.

Step 5: Summarize the data.

F. CLASSIFICATION OF THE LEVEL OF OPPORTUNITY TO CHANGE FROM THE SCCM TO THE 4CM.

The authors used information from the focus group and input parameters with their levels to generate a classification tree of the levels of possibility to change from the SCCM to the 4CM for the current network situation. The steps for creating a classification tree are as follows.

Step 1: Use the criteria for the level of possibility to change from the SCCM to the 4CM to divide situations (43 factorial experiments) into five classes.

Step 2: Generate a classification tree to determine the level of possibility to change from the SCCM to the 4CM for the case study using the ID3 algorithm of Quinlan [49] based on the data set obtained from Step 1 to test each attribute at every tree node. The ID3 algorithm generates the classification tree by performing a top-down, greedy search for locally optimal entropy values with no backtracking.

IV. CASE STUDY

Real-life instances involving four jobs in horizon planning over 20 periods were tested, and these cases were provided by a transportation company in Thailand. Four transportation chains were considered. The job descriptions used in the case study are given in Table 4.

TABLE 4. Job descriptions in the case study.

Job no.	Loading terminal	Unloading terminal	e_j (Date)	l_j (Date)
1	Terminal 1	Terminal 7	1	6
2	Terminal 3	Terminal 5	3	8
3	Terminal 4	Terminal 6	4	9
4	Terminal 8	Terminal 2	2	7

e_j =Earliest allowed arrival time of job j, l_j = Latest allowed arrival time of job j

The physical locations of different nodes and the relationships among organizations in the multiple transportation chains in the case study are shown in Figs. 8 and 9.

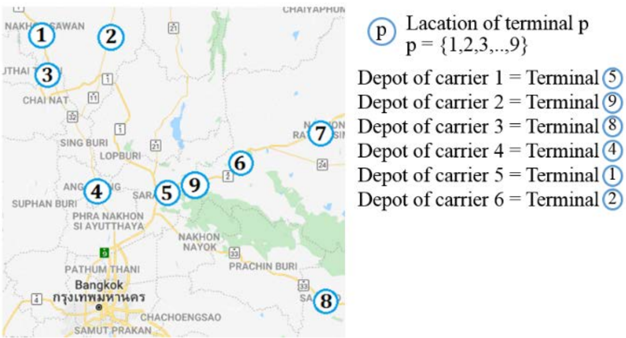

FIGURE 8. Locations of all terminals in the case study.

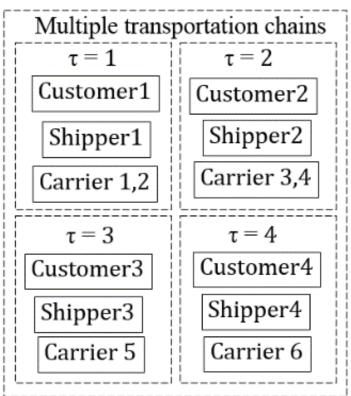

FIGURE 9. Relationships among organizations in the multiple transportation chains in the case study.

Input parameters, such as the penalty cost, capacity of vehicles, variable cost for the control tower, fixed cost for the control tower, management cost when using the SCCM, and the ability to accommodate trucks at each terminal, are shown in Table 5.

V. RESULTS AND DISCUSSION

A. THE COMPUTATIONAL RESULTS OF THE PROPOSED METHODS AND THE RESPONSE DATA

The experiments were run on a PC with an AMD Ryzen 5 4600H CPU 3.00 GHz and 16 GB RAM. The feasible route generation step of the proposed method was coded in JavaScript in NetBeans IDE 8.1. Then, OpenSolver 2.9.4 based on the branch and cut algorithm was used to solve the model formulation. Although the proposed method provided the optimal solution, the optimal solution may not be guaranteed when the algorithm stops before finding the optimal solution. Therefore, the results obtained from the proposed method were compared with the lower bound achieved by relaxing the integrality Constraint (13) of the model formulation to verify the effectiveness of the proposed method when the algorithm stopped before finding the optimal solution. We defined Gap as the difference percentage between the total cost and the lower bound for the SCCM and the 4CM, calculated from the following equation: Gap (%) = [Objective Value - Lower Bound]/Objective Value ∗ 100%) [50]. Table 6 shows the comparison of the proposed method with the lower bounds and response variables obtained from a single replicate of 43 experimental designs (situations).

TABLE 5. Input parameters.

Constant parameters	Value
Capacity of vehicles	25 tons per trip
Penalty cost	1,500 baht/trip/day
The cost of transportation control for the control tower	200 baht/trip
The coordinated decision-making cost for the control tower	10,000 baht/20 periods
Management cost when using the SCCM	12,739 baht/transportation chain
Ability to accommodate trucks at each terminal	50 trips/day

Table 6 indicates that the proposed method is sufficiently efficient in solving the CBMVRP because the percentage Gap between the total cost and the lower bound of the SCCM and 4CM for all experiments was less than 0.6%. For this case study problem, we could not conclude that the 4CM increased the computation time because the 4CM decreased the computation time of situation numbers 1, 3, 5, 7, 22, 34, 38, 39, and 41 when compared with the SCCM. It seems that the problem size was too small to differentiate between the computation times of the 4CM and SCCM. Although the proposed method could not find the optimal solution for some experiments within the given time and conditions, a result obtained from the proposed method was close to the lower bound for all experiments (Situation No). Additionally, the response data obtained from this method are statistically analyzed and displayed in the following subsection.

B. STATISTICAL ANALYSIS OF THE EFFECTS OF PARAMETERS

The central composite design (CCD) with one center point and five uncertain input parameters is used to determine the impact of the 4CM and the effects of the parameters on transportation performance, including the percentage

TABLE 6. Comparison of the proposed method with the lower bounds and observed response variables.

Situation No.	Input parameters					CPU time (Seconds)		Gap (%)		Response variables		
	A	B	C	D	E	SCCM	4CM	SCCM	4CM	GTC (%)	GSC (%)	GCC (%)
1	11.10	1.00	0.10	80	5	**6.22**	**2.41**	0.20	0.05	16.80	18.03	16.40
2	30.00	1.00	0.10	80	5	**35.05**	200.11#	0.21	0.03	16.65	14.66	16.90
3	11.10	10.00	0.10	80	5	**6.23**	**2.74**	0.20	0.05	16.80	18.03	16.40
4	30.00	10.00	0.10	80	5	**34.78**	201.15#	0.21	0.03	16.65	14.66	16.90
5	11.10	1.00	1.00	80	5	**1.29**	**1.09**	0.11	0.02	16.13	22.00	14.01
6	30.00	1.00	1.00	80	5	**1.16**	**1.46**	0.02	0.03	12.56	40.95	7.02
7	11.10	10.00	1.00	80	5	**1.28**	**0.77**	0.11	0.02	16.13	22.00	14.01
8	30.00	10.00	1.00	80	5	**1.17**	**1.48**	0.02	0.03	12.56	40.95	7.02
9	11.10	1.00	0.10	170	5	MT	MT	0.15	0.05	9.32	-8.24	16.44
10	30.00	1.00	0.10	170	5	MT	MT	0.14	0.02	13.38	-5.54	16.45
11	11.10	10.00	0.10	170	5	MT	MT	0.15	0.05	9.32	-8.24	16.44
12	30.00	10.00	0.10	170	5	**892.53**	MT	0.14	0.02	13.38	-5.54	16.45
13	11.10	1.00	1.00	170	5	**1.41**	**34.39**	0.09	0.03	8.63	-7.66	15.43
14	30.00	1.00	1.00	170	5	**1.52**	MT	0.04	0.03	11.73	3.01	13.31
15	11.10	10.00	1.00	170	5	**1.41**	**34.5**	0.09	0.03	8.63	-7.66	15.43
16	30.00	10.00	1.00	170	5	**1.51**	MT	0.04	0.03	11.73	3.01	13.31
17	11.10	1.00	0.10	80	35	MT	MT	0.28	0.09	16.48	15.51	16.79
18	30.00	1.00	0.10	80	35	MT	MT	0.26	0.02	16.76	16.16	16.83
19	11.10	10.00	0.10	80	35	MT	MT	0.28	0.09	16.48	15.51	16.79
20	30.00	10.00	0.10	80	35	MT	MT	0.26	0.02	16.76	16.16	16.83
21	11.10	1.00	1.00	80	35	**0.86**	**1.57**	0.00	0.00	8.67	15.51	6.17
22	30.00	1.00	1.00	80	35	**1.59**	**1.90**	0.28	0.00	7.62	15.51	6.55
23	11.10	10.00	1.00	80	35	**0.93**	**1.56**	0.00	0.00	8.67	15.51	6.17
24	30.00	10.00	1.00	80	35	**1.51**	**4.18**	0.28	0.00	7.62	15.51	6.55
25	11.10	1.00	0.10	170	35	MT	MT	0.16	0.03	12.39	1.62	16.76
26	30.00	1.00	0.10	170	35	MT	MT	0.20	0.02	14.93	1.62	16.92
27	11.10	10.00	0.10	170	35	MT	MT	0.16	0.03	12.39	1.62	16.76
28	30.00	10.00	0.10	170	35	MT	MT	0.20	0.02	14.93	1.62	16.92
29	11.10	1.00	1.00	170	35	**0.95**	**1.05**	0.00	0.00	4.87	1.62	6.36
30	30.00	1.00	1.00	170	35	**1.45**	**1.50**	0.09	0.00	5.82	1.62	6.54
31	11.10	10.00	1.00	170	35	**0.94**	**1.05**	0.00	0.00	4.87	1.62	6.36
32	30.00	10.00	1.00	170	35	**1.40**	**1.41**	0.09	0.00	5.82	1.62	6.54
33	11.10	5.50	0.55	125	20	MT	MT	0.18	0.02	10.02	5.79	11.62
34	30.00	5.50	0.55	125	20	MT	**9.62**	0.14	0.00	11.18	5.79	11.92
35	20.55	1.00	0.55	125	20	MT	MT	0.25	0.01	10.80	5.79	11.82
36	20.55	10.00	0.55	125	20	MT	MT	0.25	0.01	10.80	5.79	11.82
37	20.55	5.50	0.10	125	20	MT	MT	0.24	0.01	15.08	5.79	16.85
38	20.55	5.50	1.00	125	20	**1.00**	**0.88**	0.00	0.00	6.21	5.79	6.30
39	20.55	5.50	0.55	80	20	MT	**8.61**	0.33	0.05	12.33	15.51	11.74
40	20.55	5.50	0.55	170	20	MT	MT	0.14	0.02	9.83	1.62	11.75
41	20.55	5.50	0.55	125	5	**2.53**	**51.07**	0.06	0.05	12.93	15.43	12.34
42	20.55	5.50	0.55	125	35	MT	MT	0.25	0.01	10.80	5.79	11.82
43	20.55	5.50	0.55	125	20	MT	MT	0.25	0.01	10.80	5.79	11.82

= Solver found an integer solution within tolerance, MT = Solver stopped at 11 hours, Values in **bold** represent the solver has found the optimal solution.

differences in the total cost, shipper cost and carrier cost. Each factor is present at three levels, as displayed in Table 3. A normal probability plot of the effects is used to determine the magnitude, direction and importance of the effects for a CCD. In the statistical analysis of the full model, Minitab labels the statistical points, which plot toward the right or left side of the graph [51]. Figs. 8-10 display an uncertain input parameter that has a statistically significant influence on transportation performance at the 0.05 level based on GTC, GSC and GCC. Fig. 10 reveals that C, D, CE, E, AD, DE, AC, A and E^2 significantly affect GTC. AD, DE, A and E^2 have positive effects, which suggests that increasing these values increases GTC. However, when C, D, CE, E, and AC increase, GTC decreases. Fig. 11 shows that D, DE, CE, C, AC, A and AE significantly affect GSC. DE, C, AC and A have positive effects, which means that increasing these variables increases GSC. However, when D, CE and AE increase, the GSC decreases. Fig. 12 indicates that C, CE, E, AE, AC and CD have significant effects on GCC. AE and CD have positive effects. When AC and CD change from low to high, GCC increases. C, CE, E and AC have negative effects. Thus, when C, CE, E and AC increase, GCC decreases. Figs. 8-10 clearly show that C, CE and AC have significant effects on all responses. However, A, D and DE have a significant effect on GTC and GSC; E has a significant effect on GTC and GCC; AE has a significant effect on GSC and GCC; AD has a significant effect on GTC; CD has a significant effect on GCC; and B, A^2, B^2, C^2, D^2, AB, BC, BD and BE are not significant for any response variable. However, there were many terms that were not significant because the p value was less than 0.05. No square term has a significant effect on GSC and GCC.

Based on Figs. 10-12, we considered only the significant effects on each response variable for adequate interpretation [45]. The regression model is now reduced and fits with the experimental data for GTC, GSC and GCC. The impact of the 4CM on GTC, GSC and GCC can be formulated as shown in (26)-(28).

$$\begin{aligned} GTC = {} & 25.62 - 0.1772\,A + 1.211\,C - 0.10136\,D \\ & - 0.2487\,E + 0.00557\,E^2 - 0.1073\,AC \\ & + 0.002225\,AD - 0.2452\,CE + 0.0007\,DE \end{aligned} \tag{26}$$

$$\begin{aligned} GSC = {} & 41.15 + 0.194\,A + 3.53\,C - 0.3388\,D \\ & - 0.260\,E + 0.436\,AC - 0.01248\,AE \\ & - 0.3707\,CE + 0.005357\,DE \end{aligned} \tag{27}$$

$$\begin{aligned} GCC = {} & 18.20 - 0.0556\,A - 3.99\,C - 0.00412\,D \\ & - 0.0475\,E - 0.1361\,AC + 0.00413\,AE \\ & + 0.0254\,CD - 0.2339\,CE \end{aligned} \tag{28}$$

The reduced models for GTC, GSC and GCC are significant because their p-values are less than 0.05, as shown in Table 7. The R^2 values indicate that the reduced models for all responses provide a satisfactory fit. The adjusted R^2 value for each response signifies that the experimental data are adequately explained by the reduced models. The predicted R^2 value indicates that the reduced models for all responses do not overfit the data.

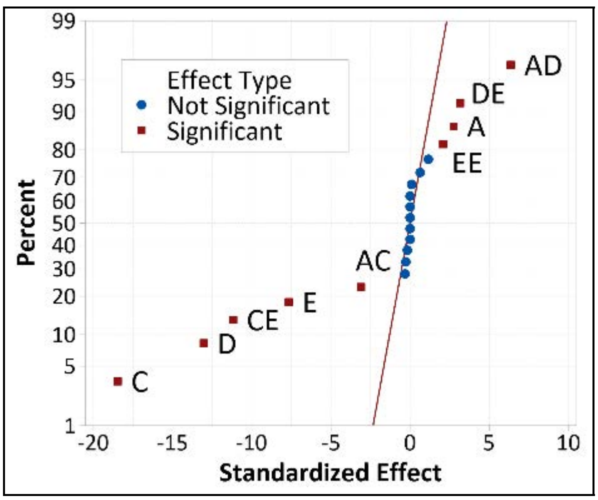

FIGURE 10. Normal plot of the standardized effects on GTC.

C. EFFECTS OF SIGNIFICANT PARAMETERS ON GTC

Fig. 13 presents interaction plots for GTC that provide the impact of the 4CM when significant input parameter changes are obtained from the regression model. The 4CM has the potential to reduce the total cost when compared to the SCCM in all situations. The AC interaction indicates that C has little effect at low A values but a large positive effect at high A values. The AD interaction plot indicates that D has a large effect at low A values but a negative effect at high A values. The CE interaction suggests that the C effect is large when E is at a high level and small when E is at the center point or a low level. The DE interaction indicates that D has a large effect on the level of E. In addition, E in the interval between 20 and 35 has a very small effect on D at all levels, but E at low levels has a large effect on D at all levels.

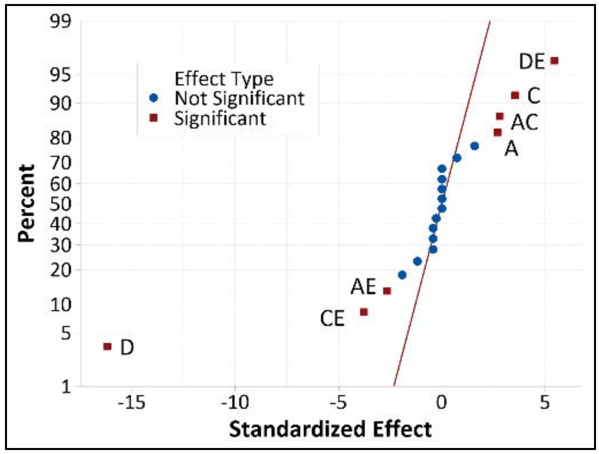

FIGURE 11. Normal plot of the standardized effects on GSC.

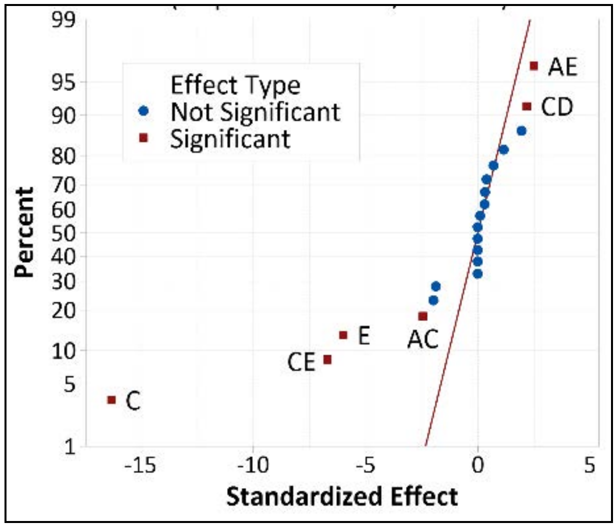

FIGURE 12. Normal plot of the standardized effects on GCC.

TABLE 7. Model summary for each response of the reduced models.

Responses	S	R^2	R^2 (adj.)	R^2 (pred.)	P value
GTC	0.71	97.02%	96.20%	95.08%	0.000
GSC	3.58	91.72%	89.77%	86.61%	0.000
GCC	1.34	91.57%	89.59%	86.26%	0.000

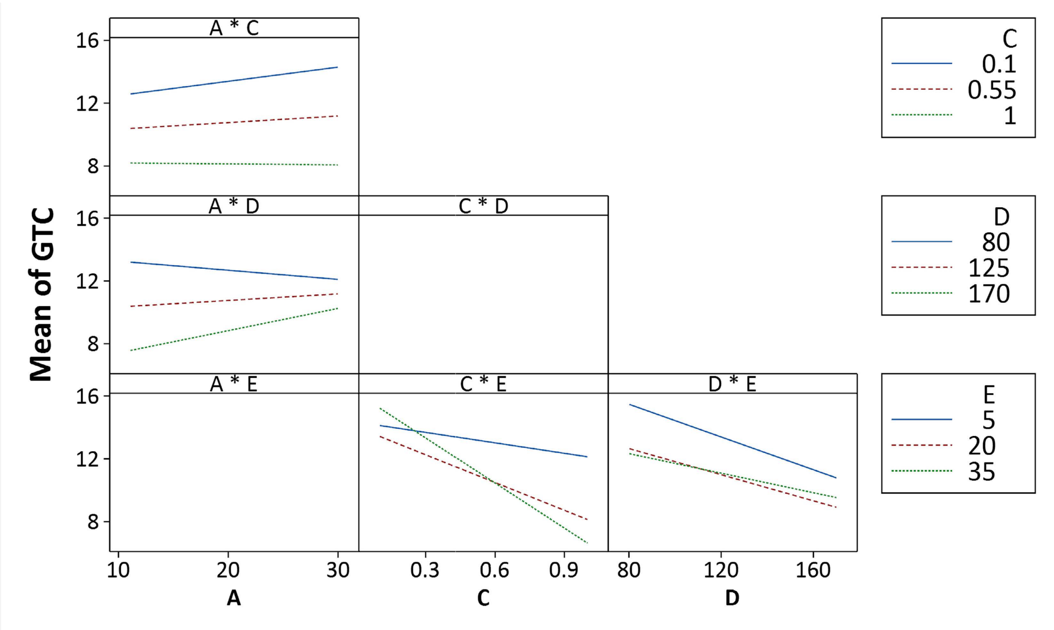

FIGURE 13. Interaction plots for GTC.

D. EFFECTS OF SIGNIFICANT PARAMETERS ON GSC

In this section, the interaction plots for GSC illustrate the impact of the 4CM when significant input parameters change. Fig. 14 shows that the 4CM has the potential to reduce shipper costs when compared to the SCCM in most situations when the significant parameters change, except in cases where there is a high demand for each job and the number of vehicles is not sufficient to meet the demand, which may cause the shipper costs when using the 4CM to be higher than the shipper costs when using the SCCM. The AC interaction indicates that C has little effect at low A values but a large positive effect at high A values. The AE results indicate that A has a small effect when E is at a high level and a larger effect when E is at the center point or a low level. The CE interaction suggests that the effect of C is very small when E is at a high level and larger when E is at the center point or a low level. The DE interaction indicates that GCC is very sensitive to D at all levels of E. When D is at a high level, regardless of the level of E, the 4CM is less effective than the SCCM.

E. EFFECTS OF SIGNIFICANT PARAMETERS ON GCC

In this section, the interaction plots for GCC provide the impact of the 4CM when the input significant parameters change, as in the previous section. Fig. 15 indicates that the 4CM has the potential to reduce carrier costs when compared to the SCCM for all situations. The plot of the AC interaction shows that GCC is insensitive to A if C is at the central point or a low level but sensitive to A if C is at a high level. The AE interaction plot indicates that E has a large effect at low A values but a negative effect at high A values. The CD and CE interactions indicate that GCC is very sensitive to C at all levels of D and E. Additionally, D and E have little effect at low C values but a large effect at high C values.

F. THE FOCUS GROUP RESULTS

We summarized the responses of the respective company representatives in the focus group discussion and presented them separately according to the following questions.

Result of question 1: All participants agreed that the 4CM would help reduce overall costs and increase the level of competitiveness. Although the 4CM was attractive, in some situations, it may not be an appropriate choice.

Result of question 2: In the case of some carriers who were assigned less work, switching from the SCCM to the 4CM was not a concern for the participants, and this problem did not affect the decision to switch from the SCCM to the 4CM for the following reasons: 1. The shipper solved this problem by looking for off-network jobs closer to the carrier's depot to provide carriers with jobs during their free time when they were assigned less work than other carriers. This solution was already in use with the SCCM and should be applied to the 4CM as well. 2. All companies must enter into an acceptable cost-sharing agreement for *c* value, so carriers understood this limitation very well and accepted it, even with fewer assignments.

Results of questions 3 and 4: Participants set the decision criterion for switching from the SCCM to the 4CM: shipping costs and carrier costs must be greater than 10% for the network company to switch from the SCCM to the 4CM. However, if they are less than 10%, the company may not be sure. However, if shipper costs or carrier costs are below 0%, the company will be reluctant to change. There will likely be significant obstacles to switching from the SCCM

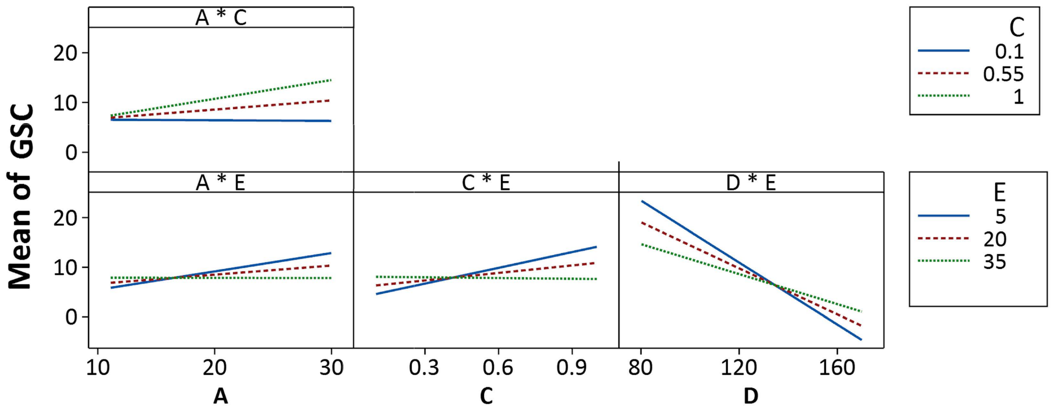

FIGURE 14. Interaction plots for GSC.

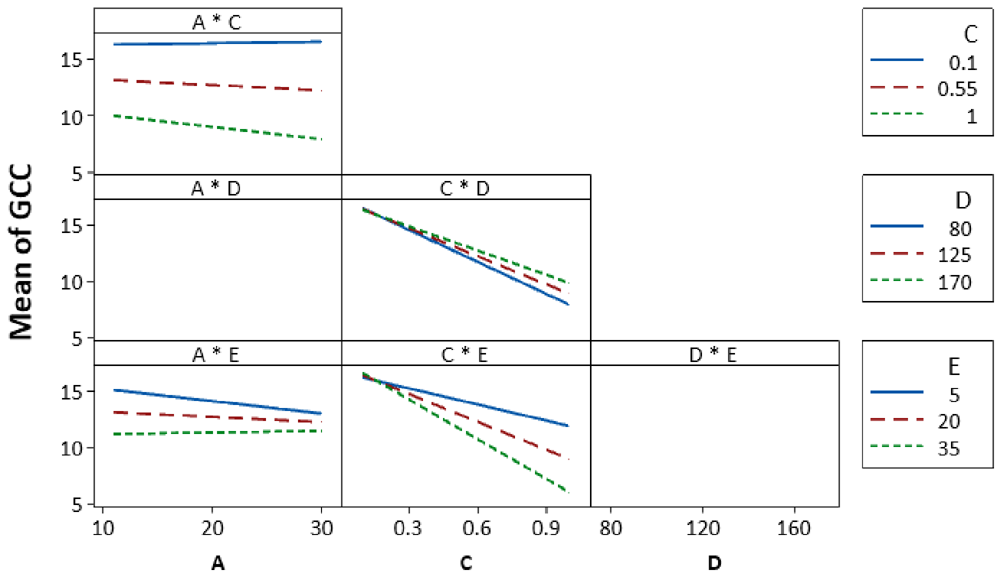

FIGURE 15. Interaction plots for GCC.

to the 4CM, where participants have set decision criteria. The likelihood of changing from the SCCM to the 4CM for the case study was at Level 5 on the scale, as shown in Table 8.

G. CLASSIFICATION TREE OF THE LEVELS OF POSSIBILITY OF CHANGING FROM THE SCCM TO THE 4CM FOR EACH SITUATION

Based on the summary information obtained from the focus group in Table 8 and the data set in Table 6, we created a classification tree to assess whether the case study situation was at any level of possibility to change from the SCCM to the 4CM class, as shown in Fig. 16.

In Fig. 16, the internal node represents a "test" of an attribute (input parameters: A, C, D, and E), in which the branch of the internal node has three levels: high, moderate, and low. Holding costs (B) were not included in this classification tree because holding costs did not significantly affect transportation performance. Each leaf node represents a class label of the level of possibility to change from the SCCM to the 4CM for the case study. The routes from root to leaf represent classification rules for the levels of possibility to change from the SCCM to the 4CM for each situation. This classification tree is a tool to make it easier for decision makers to assess the possibility level of the case study network transition to the 4CM when networks are using the SCCM. Decision makers may select the most frequent situations to assess the level of possibility that will result in a change from the SCCM to the 4CM. For example, if the case study network had the following scenarios: low demand and low C, the case study network would be classified as Class 1, indicating that there was a high probability of switching from the SCCM to the 4CM. Those involved should immediately change to the 4CM, as it offers a high chance of success and is worth the investment. The levels of possibility to switch to the 4CM for classes 2-4 are in descending order. The lower the level of change possibility, the more likely decision makers

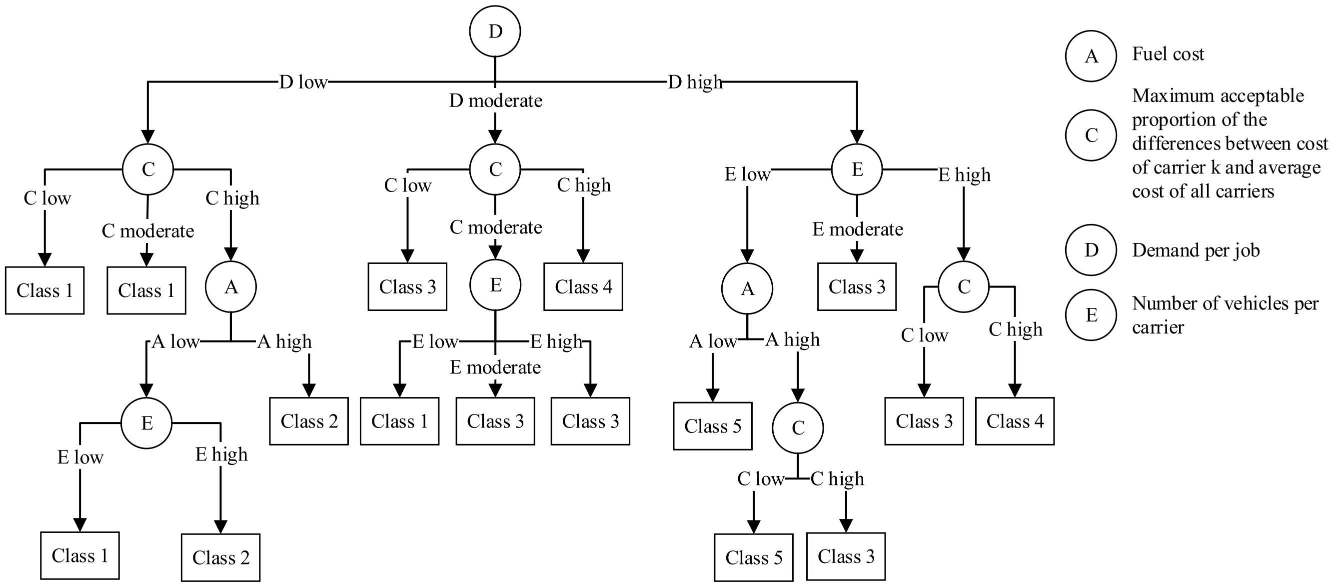

FIGURE 16. Classification tree of the probability level of changing from the SCCM to the 4CM of a case study.

TABLE 8. Summary information obtained from a focus group.

Class	Criteria to classify	The level of possibility to change from SCCM to 4CM for the case study
1	GSC >= 10% and GCC >= 10%	very high possibility
2	GSC >= 10% and 0% < GCC =< 10%	high possibility
3	0% =< GSC =< 10% and GCC >= 10%	moderate possibility
4	0% =< GSC =< 10% and 0% =< GCC =< 10%	less possibility
5	GSC < 0% or GCC < 0%	impossibility

will need to find a cost improvement method to allow the owners of each company to cooperate in the transition to the 4CM. However, assessing the case study situation as being in Class 5 would indicate that stakeholders do not need to switch to the 4CM because this model would not benefit them economically.

We summarize the results of this paper as insights into the following details.

- Although 4CM makes most of the transportation performance higher if customer demand is high and the number of vehicles in the network is low, shippers have to hold their cargo longer, increasing their costs.
- The maximum acceptable proportion of the differences between the cost of each carrier and the average cost of all carriers (c) had significant effects on the total cost, the cost of shippers and the cost of carriers. Parameter c is a value used to determine cost-sharing between carriers, and all stakeholders can customize this parameter in their cooperation contracts. Therefore, decision-makers must pay great attention to this parameter for all parties to get the best benefit.
- Most of those involved in this case study were unaware of the benefits of switching to 4CM, leaving them afraid to change their business model. For the above reasons, it has become a major obstacle that prevents this case study from changing from SCCM to 4CM. But once those involved realized the benefits of using 4CM, the barriers that existed were reduced.
- The possibility of changing from SCCM to 4CM is based on reducing shipper costs and carrier costs when using 4CM.

Consequently, these insights provide a guideline for decision-makers to implement the appropriate collaboration model for real-world industrial situations where factors are uncertain.

VI. CONCLUSION

In this paper, the impacts of a cross-chain collaboration center model (4CM) on transportation performance were investigated and compared with those of an SCCM. The comparison included the percentage differences in the total cost (GTC), shipper cost (GSC) and carrier cost (GCC) by employing a CCD with a set of 43 experiments and five uncertain input parameters, including the fuel cost (A), holding cost (B), maximum allowance of the difference between the cost of each carrier and the average cost of all carriers (C), demand of each job (D) and number of vehicles per carrier (E). Note that if GTC, GSC, and GCC are less than 0, then the performance of 4CM is lower than that of SCCM. Otherwise, the performance of 4CM is better. We proposed an ILP model based on route representations to solve the bidirectional multi-period vehicle routing problem of the proposed 4CM and SCCM in the context of bulk transportation in Thailand. A regression model of important parameters and interactions was presented, and the R^2 value, adjusted R^2 value and predicted R^2 value of all responses were close to 100%, indicating that all reduced models were acceptable for these data. Interaction plots provide assistance in establishing decision-making guidelines and promoting cross-chain collaboration among multiple transportation chains.

The statistical results showed that C, CE and AC had significant effects on all responses. The statistical results showed that certain terms affect certain responses, with the following details:

- The impact of 4CM on the total cost: As factors AD, DE, A, and E^2 increase, the difference between 4CM's total cost and SCCM's total cost significantly increases, while the difference between 4CM's total cost and SCCM's total cost significantly decreases.
- The impact of 4CM on the cost of shippers DE, C, AC and A has positive effects, which means that increasing these variables increases the difference between the 4CM's shipper cost and the SCCM's shipper cost. However, when D, CE and AE increase, the difference between the shipper cost of the 4CM and that of the SCCM decreases.
- The impact of 4CM on the cost of carriers: When AC and CD change from low to high, the difference between 4CM's carrier cost and SCCM's carrier cost increases. While C, CE, E and AC increase, the difference between 4CM's carrier cost and SCCM's carrier cost decreases.

In computational experiments with real-world instances when considering transportation performance in terms of reducing the total cost, we found that the 4CM achieved total cost savings in the range of 4.87–16.80% compared to the SCCM. Regarding transportation performance in terms of reducing carrier costs, we found that the 4CM achieved carrier cost savings in the range of 6.17–16.92% compared to the SCCMs. For transportation performance in terms of reducing shipper costs, we found that the 4CM can reduce shipper costs in the range of –8.24 to 40.95% compared to the SCCM. It was clear that the 4CM can better reduce the total cost and carrier cost for all situations compared to the SCCM. The 4CM was highly effective in terms of reducing shipper costs in most situations. In the case of high demand where the total number of vehicles in the network is low, shipper costs increased, resulting in the SCCM performing better in shipper costs than the 4CM. Because fewer trucks discharge goods from warehouses relatively slowly, shippers must hold goods longer. They must pay for storing these goods as long as they are still in the warehouse, which was consistent with research by Mrabti *et al.* [27] showing that the storage cost is higher when compared before and after the pooling scenario.

Furthermore, we convened a focus group to collect data about the possibility and criteria for changing the case study network from an SCCM to a 4CM and then used the ID3 algorithm to create a classification tree of the levels of possibility to change from the SCCM to the 4CM for each situation. The results of the focus group discussion and classification tree were as follows:

- Participants were made more aware of the meaning and benefits of the 4CM by participating in the focus group discussion because the moderators explained important 4CM information to them before the meeting.
- Once the focus group discussion participants knew about the benefits of the 4CM, they were interested in using it.
- In this case study, the possibility levels for changing from the SCCM to the 4CM used shipper and carrier costs as classification criteria.
- Switching from the SCCM to the 4CM will require considerable effort, as participants determined that shipper and carrier costs should be at least 10% more economical to justify changing the business model. However, if the 4CM can save more than 0%, there is still a minimal chance of changing from the SCCM to the 4CM.
- The classification tree presented in this paper provides a tool for transport operators of this case study to assess the possibility of transition from the SCCM to the 4CM and decide on the appropriate strategy.

Therefore, the 4CM is suited to collaboration among participants who already have many or sufficient trucks to meet customer demands. However, the opportunity to increase the level of collaboration between networks depends on the criteria that classify the level of possibility of switching to the 4CM that all stakeholders set for themselves, and each case study may have different classification criteria. We expect this research to guide decision-making in enhancing the level of collaboration to improve the total system efficiency for transport operators in Thailand.

In the future, we will propose more complex technologies and concepts for cross-chain collaboration center, such as profit compensation if some companies profit less than others in the collaborative transportation network, information sharing through blockchain technology. Moreover, we will also offer a new method to solve the multi-objective collaborative vehicle routing problem with transportation time uncertainty to obtain a good solution quality and acceptable computation time for large and medium instances, which will extend to more complex problems.

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