Improving Freight Transport Mobility and Efficiency via Synchronization

Final Report

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16. Abstract

A critical operational issue in the integrated vehicle routing and scheduling problem with cross-dock (IVRSPCD) is disruption to enroute pickup vehicles due to traffic accidents or mechanical failures. Such disruptions are not uncommon in practice and have widespread negative impacts on the system, including late vehicle arrivals to suppliers, cross-dock (CD), and customers, modification of cross-dock (CD) operational plans, and increased transportation costs for the carrier. This study contributes to the IVRPCD literature by proposing a reactive recovery system that integrates the routing of vehicles and scheduling in response to the breakdown of a pickup vehicle to mitigate the negative impact of such disruptions. To this end, a model is developed using an iterative information exchange (IIE) protocol between drivers, the dispatcher, and the CD operator to synchronize vehicle arrivals at the CD. The reactive recovery system consists of two main components: an integrated vehicle routing and scheduling model for normal conditions (IVRSPCD-normal) and one for disruption conditions (IVRSPCD-disruption). To demonstrate the effectiveness of the developed IVRSPCD models, numerical experiments are performed on a hypothetical network. Results from the numerical experiments showed that the proposed IIE protocol is effective in lowering the makespan and total delay in the event of a disruption. The CD makespan is primarily affected by the start time of the vehicle breakdown and communication delay. The delay at the supplier locations is affected by both the number of unserved nodes due to vehicle breakdown and the start time of the vehicle breakdown and communication delay. The same is true for the delay at the customer locations; however, there is an additional interaction effect between the two variables. The same finding applies to the case where the delay for both suppliers and customers is considered.

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Executive Summary

The objective of this study is to develop a protocol to synchronize the decisions of a truck dispatcher, drivers, and cross-dock operator in the event of a disruption. The benefit is that the synchronization of the independent decisions from individual stakeholders/models will minimize the impact of a disruption on cross-dock (CD) operations and service delay at the suppliers and customers. Additionally, it will facilitate the future adoption of edge computing or distributed systems. Another advantage of the proposed synchronization method over previously proposed integrated systems is the ability to tackle large-scale problems efficiently while achieving individual stakeholder objectives. Lastly, individual models could be updated or replaced separately with less cost compared to updating a single integrated model.

Two separate models are used in this study; they were previously developed but extended for this particular study. The first model addresses the routing decisions in the network and is referred to as the VRPCD model. The VRPCD model takes the product requirements and the service time window of suppliers and customers and determines the routes for Inbound Trucks (ITs) and Outbound Trucks (OTs). The second model is a CD model that determines the dock door assignment, product transfer from inbound to outbound area, and the latest departure time of OTs given arrival times and product requirements ITs and OTs, and a set of inbound and outbound dock doors. To synchronize the VRPCD model and the CD model, an Iterative information Exchange (IIE) protocol is developed. The IIE protocol aims to make the assumed CD operational time from the VRPCD model as close to the actual CD operational time provided by the CD model. To achieve this, the IIE protocol runs the VRPCD and CD models sequentially and iteratively exchanges information between them until the solutions from the two models converge.

Three sets of analyses (Analyses I, II, and III) were performed to evaluate the usefulness of the IIE method and the impact of vehicle breakdown on the IVRSPCD network. Analysis I compared the results from the conventional VRPCD model with the proposed IIE method. Analyses II and III assessed how a vehicle breakdown affects the CD, suppliers, and customers. Results from the numerical experiments showed that the proposed IIE protocol is effective in lowering the makespan and total delay in the event of a disruption. The CD makespan is primarily affected by the start time of the vehicle breakdown and communication delay. The delay at the supplier locations is affected by both the number of unserved nodes due to vehicle breakdown and the start time of the vehicle breakdown and communication delay. The same is true for the delay at the customer locations; however, there is an additional interaction effect between the two variables. The same finding applies to the case where the delay for both suppliers and customers is considered.

CHAPTER 1
Introduction

Cross docking is a logistics strategy where goods from the suppliers are transported to an intermediate transshipment point via inbound vehicles, called the cross-dock (CD), before being delivered to the customers via outbound vehicles. The cross-docking system provides two advantages over the traditional warehouse system. First, cross-docking system (CD-system), by design, replaces two costly and time-consuming tasks found in the traditional warehouse system: storing and picking. Second, the CD-system sends materials to customers in small batches with correct order to facilitate just-in-time production. The implementation of cross-docking requires coordination of operation both at network and local level. The local level includes any operations performed at the CD and any operations performed elsewhere in the network is considered as network level. As a result, the cross-docking system give rise to different level of decision making problems such as strategic (e.g., location of CD terminal(s), layout of terminal), tactical (e.g., dock door specification, equipment and workforce capacity planning), and operational (e.g., vehicle routing, vehicle scheduling, dock-door assignment, (un)loading (in)outbound trailers, scheduling of CD equipment and workforce, planning for staging area). Though most of these decision problems were explored separately, there is an inherent interdependency between the operational decisions made at the local and network levels. Thus, cross-docking logistic strategy requires careful coordination of operations to make it cost-effective and efficient. As such, there is need for integration and synchronization of these operational decision problems (Buijis et al., 2014). This study focuses on coordinating two important operational decisions in the distribution network, vehicle routing and CD scheduling.

Previous studies developed models to integrate vehicle routing and scheduling problem with cross-docking (IVRSPCD). Some of these studies developed models for routing of both inbound and outbound vehicles (Dondo and Cerdá, 2014; Dondo and Cerdá, 2015; Yin et al., 2016) while other studies only include routing decisions for either inbound vehicles (Liao, 2021b) or outbound vehicles (Buijis et al., 2014; Enderer et al., 2017; Liao, 2021a). All of these studies integrated vehicle routing with different operational aspects of vehicle scheduling at CD such as consolidation to reduce inventory holding cost (Buijis et al., 2014), assignment of vehicles to dock-doors (Dondo and Cerdá, 2014; Dondo and Cerdá, 2015; Enderer et al., 2017; Liao 2021a; Liao 2021b; Rahbari, 2019; and Ying et al., 2016) sequencing of vehicles at each dock-door (Dondo and Cerdá, 2014; Dondo and Cerdá, 2015; and Ying et al., 2016), and time to transfer products between strip and stack doors (Enderer et al., 2017). All of previous IVRSPCD assumed that the no interruptions occur during the execution of the routing and scheduling plans. In practice, disruptions such as traffic accidents or mechanical failure of trucks are quite common. The disruption in vehicle routing problem (VRP) has been studied extensively while in vehicle routing problems with a cross dock are scarce. Ahmed et al. (2024) studied the VRPCD with inbound truck (IT) breakdown and quantified the impact of such disruption for CD, suppliers and customers, and logistic service providers. However, a gap in the literature is that none of the prior IVRSPCD studies have considered disruption to inbound trucks (ITs) or outbound trucks (OTs).

Two important practical operational issues, to the best of our knowledge, have not been addressed in the IVRSPCD problem. The first is to obtain a feasible truck routing and operations to support these truck schedules and product consolidation within the CD. Obtaining a feasible solution requires careful synchronization of routing and scheduling. Synchronization of vehicle routing and CD scheduling is necessary for a few important reasons. First, to improve the efficiency of the network. Traditionally, vehicle routing and scheduling are done separately and the vehicles are processed on a First Come First Serve basis at the CD. The lack of synchronization may lead to long waiting times and early/tardy jobs at the CD (*1*). Second, to make informed decisions leveraging data interdependency between vehicle routing and scheduling (*2*). The vehicle routing problem provides information on the quantity and type of goods transported by IT as well the vehicle arrival times at the CD. This is an important data set for the vehicle scheduling problem. On the other hand, the departure times of OTs from the CD are defined by the vehicle scheduling problem. With the knowledge of the departure times, the vehicle routing problem can modify the routing of OTs and service time for customers. The second is to cope with disruption. In the event of a disruption, the decision-maker can still follow the original plan, but this will result in infeasible routes for the disabled IT and OTs will not have products to serve the customers. Thus, it will diminish the synchronization of operations within CD. The uncertainty in arrival times of disabled IT can make the entire optimized operations inefficient. Alternatively, in such a scenario, real-time decision-making leveraging information exchange can be useful. A new routing plan could be developed that reroutes some of the enroute trucks and/or dispatch a new truck from the CD to pick up freight from all the suppliers and adjust the routes of OTs. The routing planner updates the CD about the change in arrival times and the CD takes a recourse or makes adjustments to its operations. Then, the CD relays the updated plan to the routing planner to revise their OT routing schedule. Previous IVRSPCD models did not allow the opportunity for information exchange between individual models. This research proposes an iterative information exchange protocol for routing and scheduling decisions to minimize the impact of a disruption on CD operations and service delay at the suppliers and customers.

The objective of this study is to develop models to synchronize decisions of vehicle routing and scheduling under normal and disruption conditions where synchronization is performed using an iterative process of information exchange between individual models. This model is referred to as the Synchronized Vehicle Routing and Scheduling Problem with Cross-dock (SVRSPCD). The benefit of SVRSPCD is that the independent decisions from individual models from the routing planner and the CD will facilitate the future adoption of edge computing or distributed systems. Another advantage of this system over integrated systems is the ability to tackle large-scale problems in a short period of time while achieving individual objectives. Additionally, individual models could be updated or replaced separately with less cost compared to updating a single integrated model. The second objective is to quantify the impact of disruptions on transportation costs and delivery delays. In this study, the disruption incident considered is an enroute inbound truck being out of commission. Numerical experiments are performed on a small-sized hypothetical network to demonstrate the effectiveness of the developed synchronized models.

The contributions of this study to the VRPCD literature are:

- Including disruptions in IVRSPCD: While disruptions due to vehicle breakdown have been studied for VRP and VRPCD, to the best of the authors' knowledge, this study is the first to consider a vehicle breakdown for the IVRSPCD.

- Developing communication scheme for IVRSPCD: While previous studies developed a combined mathematical model for IVRSPCD, this study considers vehicle routing and scheduling at CD problem separately for routing planner and CD. Instead of a combined mathematical model, synchronization is performed using information exchange.

- Developing insights into the impact of disruptions: This is the first study to quantify the impact of disruption due to vehicle breakdown on service quality and CD operations in IVRSPD.

The rest of this report is organized as follows. Chapter 2 provides a review of related studies on the IVRSPCD studies. Chapter 3 provides the problem description and methods proposed to solve the models. Chapter 4 discusses the numerical results and findings. Lastly, Chapter 5 provides concluding marks.

CHAPTER 2
Literature Review

Previous literature that combines vehicle routing and cross-docking logistic strategy can be divided into two groups: (1) Vehicle routing with cross-docking (VRPCD) and (2) integrated vehicle routing and scheduling problem at a CD (IVRSPCD). The literature related to IVRSPCD is summarized in Section 2.1. Section 2.2 summarizes previous studies where disruption scenarios are considered in VRP.

2.1 Models and Solution Approaches for VRPCD Under Normal Conditions

The first IVRSPCD was formulated by Agustina et al. (2014). The authors formulated a MILP model for food retailers to minimize total costs. Though the integrated model considers vehicle scheduling on both the inbound and outbound side, the vehicle routing decisions are made only for outbound vehicles in the delivery process. The model is solved in CPLEX and the size of the solution space is reduced using the concept of customer zones instead of individual customers. Donde and Cerdá (2014) developed a monolithic MILP model integrated vehicle routing and vehicle scheduling with a limited number of dock doors. Thus, in addition to the routing decision, the proposed model determined the dock door assignment and sequence of vehicles at each dock door. The authors improved the computation efficiency of the solution to the model by incorporating constraints that resemble the VRP-sweep method into the problem formulation. Donde and Cerdá (2015) introduced MILP model for the IVRSPCD problem to simultaneously determine: the routing and scheduling of heterogeneous vehicles, dock-door assignment, vehicle docking sequence, and transfer time of goods from strip doors to stack doors. To improve the computation efficiency of the branch-and-cut search, the authors used the sweep-based MILP formulation similar to their previous study (3). Yin et al. (2016) formulated IVRSPCD model to minimize weighted transportation costs and makespan while considering restriction on CO_2 emissions and fuel efficiency in the constraints. The developed model determines routes of heterogenous vehicles to deliver fresh products within the time windows of customers. The authors used coevolution framework to solve the model. Enderer et al. (2017) formulated an IVRSPCD model to minimize the total material handling and transportation costs. This model integrated the dock-door assignment and vehicle routing by assigning suppliers to inbound doors, transferring commodities between strip and stack doors, assigning customers to stack doors, and routing vehicles from stack doors to customers. The authors used a column generation-based algorithm to solve the model. Rahbari et al. (2019) formulated a bi-objective MIP for vehicle routing and cross-dock scheduling with perishable fresh products. The model minimizes the total costs while maximizing the freshness of the products to deliver to the customers. The developed models were solved using CPLEX. Liao (2021a) developed integrated outbound vehicle routing and scheduling when the inbound schedule is fixed while Liao (2021b) developed integrated inbound vehicle routing and scheduling when the outbound schedule is fixed. In both studies, the author developed a constrained mixed integer dynamic programming model. Liao (2021a) used decomposed-based iterated local search while Liao (2021b) used a cooperative coevolutionary decomposition-based algorithm to solve the developed models.

The above review indicates that previous IVRPCD studies have examined the impact of different operational characteristics, but none has investigated the impact of disruption. This study aims to fill this gap in the literature. Another novelty of this research is the synchronization of VRPCD and scheduling at CD using information exchange among vehicles, the dispatcher, and the CD operator. This communication procedure provides the planner, vehicle dispatcher, and CD the opportunity to achieve their individual objectives while improving the resiliency of the network in response to disruptions.

2.2 Models and Solution Approaches for VRP Under Disruptions

The disruption recovery strategies used in previous VRP studies to address vehicle breakdown are shown in Figure 1. A detailed summary of disruption scenarios (i.e., node, link, facility, vehicle, or a combination of these) in VRP can be found in Eglese and Zambirinis (2018). As shown in Figure 1, four criteria for recovery are typically considered: (i) using extra vehicle(s) from the depot (strategies 1-a to 1-c) or the enroute vehicles (strategies 2-a to 2-e), (ii) whether enroute vehicles need to finish their current trips before rerouting, (iii) whether backup vehicle(s) (i.e., extra or enroute) need to visit the failed vehicle(s), and (iv) whether to serve all or a subset of the customers of failed vehicle.

Li et al. (2007) proposed a decision support system prototype for the single-depot vehicle scheduling problem (SDVSP) and rescheduling problem (SDVRSP) to deal with transit vehicle breakdown. The authors used recovery strategies 1-a and 2-a. For the VRP problem, instead of assuming a vehicle will be out of commission for the entire planning period, Zhang and Tang (2007) allowed the breakdown to occur within a certain period and defined it as the recovery time window. To reroute vehicles, they used strategy 2-c during the recovery time window, and after the recovery time-window, they used the original routing plan. Wang et al. (2009) studied the breakdown of transit vehicles and used strategies 1-b and 2-b to reroute vehicles. Yang and Wang (2009) studied vehicle disruption in VRPTW. The authors used strategy 2-b and the rescue possibility concept to reroute vehicles. Mu et al. (2011) studied the distribution of a single common product (bottled water, oil, or gas) to a set of clients when a single vehicle breaks down. The authors used recovery strategies 1-c and 2-e. Minis et al. (2012) examined a similar product distribution problem as Mu et al. (2011) with two differences. First, the vehicles deliver multiple products to unique clients. Second, the depot serves as a replenishing point for products. The authors used recovery strategy 2-d. In these studies, heuristics such as the common feasible network (CFN) based auction algorithm, Lagrangian relaxation and insertion algorithm, Genetic Algorithm, and Tabu Search have been proposed.

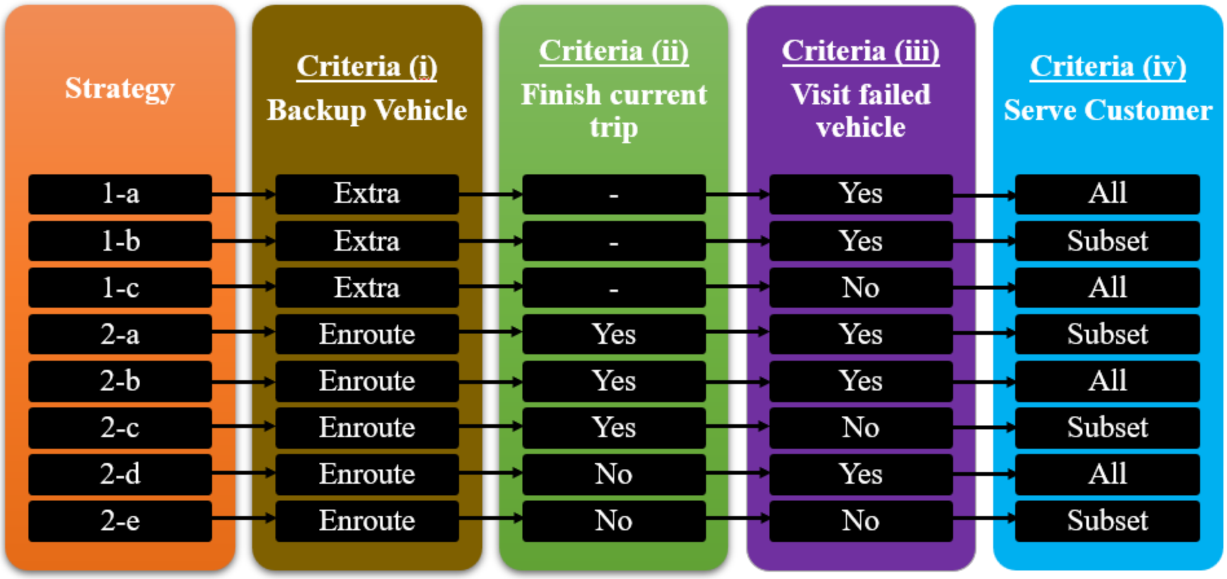


FIGURE 1. Vehicle breakdown recovery strategies in VRP.

The above literature review reveals a research gap: none of the previous studies has investigated the impact of disruptions in VRPCD. Effective disruption management is important and necessary to maintain the efficiency of the cross-docking logistic strategy and reduce the widespread negative impact on the distribution network. Thus, this study contributes to the VRPCD literature with a new disruption recovery model and deep insights into the impact of disruptions. Another notable contribution is the development of the Golden Ball heuristics to solve the VRPCD under normal conditions and disruptions.

CHAPTER 3
Methods

3.1 Problem Description

This study investigates the integrated vehicle routing and scheduling problem (IVRSPCD) in a product distribution network with multiple suppliers, multiple customers, and a single cross-dock. There are two sub-problems to the IVRSPCD: vehicle routing problem with CD (VRPCD) and vehicle scheduling problem at CD (VSPCD). The VRPCD aims to find the number of ITs and OTs and their corresponding routes while the VSPCD determines vehicle sequencing and their assignment at dock doors, product consolidation, and departure time of OT from CD. The process flow of the IVRSPCD is as follows. The OT follows the previously determined routes by the VRPCD to pick up products from suppliers before arriving at the inbound area of the CD facility to unload the products. The unloaded products are moved from inbound dock doors to either the loading area or the temporary storage area in the CD. In the outbound area, the products are consolidated and loaded into the OT before departing from the CD loaded with requested products. The OT follows the pre-determined routes to deliver products to the customers before returning to the CD. In previous studies, a single combined model was developed to integrate VRPCD and CD into IVRSPCD. In this study, separate models were utilized to determine the routes of IT and OT as well as CD operations. The iterative information exchange protocol (IIE) is proposed to synchronize the routing and CD operational decisions to find a feasible solution for the synchronized IVRSPCD problem (SVRSPCD-IIE).

3.2 Synchronized VRSPCD with Iterative Information Exchange (SVRSPCD-IIE)

Two separate models are synchronized to determine the plan for truck routing and operations within the CD. The first model addresses the routing decisions in the network and is referred to as the VRPCD model. The VRPCD model takes the product requirements and the service time window of suppliers and customers and determines the routes for IT and OT. The second model determines the dock door assignment, product transfer from inbound to outbound area, and the latest departure of OT given arrival times and product requirements IT and OT, and a set of inbound and outbound dock doors.

3.2.1 Vehicle routing/rerouting Model (VRPCD model)

The vehicle routing problem considers a distribution network with multiple suppliers with freight to be shipped, multiple customers needing freight to be delivered, and a CD for product consolidation. A fleet of homogenous IT and OT is used to execute the pickup and delivery tasks, respectively. IT leaves the CD and pick up goods from the suppliers before returning to the CD. At CD, products are consolidated and reloaded to OT. The OT departs from CD to deliver goods to the customers within a predefined time window. The VRPCD model determines the routes of IT and OT with the objective of minimizing the cost. The cost consists of penalties for late deliveries and transportation costs based on the total distance traveled. The VRPCD model makes several assumptions in determining the routes of IT and OT. The key assumptions are as follows: 1) one-to-one relationship between suppliers and customers, 2) both suppliers and customers have soft time windows; meaning a penalty is incurred when time windows are violated, 3) split shipments are not allowed, 3) planning time horizon is a 16-hour day, and 4) asynchronous arrival/departure of the IT/OT. The vehicle routing problem is well-known to be NP-hard. Therefore, large instances of the problems are computationally challenging to resolve in a short duration. In order to use the model in real-time, the modified Golden-Ball (GB-VRPCD) meta-heuristic developed by Ahmed et al., 2024 is used. The GB-VRPCD starts with a population of solutions which is divided into multiple sub-populations (team). Each team contains the routes of all IT and OT. At each iteration of the algorithm, the strength of a team (i.e., solution quality) is increased by using different techniques (e.g., 2-opt, λ-interchange) to find better IT and OT routes. The process is repeated until the termination criteria are satisfied and the final solution includes the team with the highest strength. The detailed mathematical formulation and solution heuristics of the VRPCD model can be found in (Ahmed et al., 2024).

3.2.2 Cross-dock Model (CD model)

The CD problem considers a multi-door facility that handles multiple operational tasks such as unloading products from IT, sorting, consolidating, and loading onto OT. The CD model determines the docking schedules and door assignment of IT and OT as well as product assignment given a set of IT and their arrival times, a set of OT and their “soft” departure deadlines, products loaded on IT, products needed on OT, and a set of dock doors at the CD. The objective of the CD model is to minimize the makespan and total tardiness of OT. The tardiness is modeled by a non-linear function. The non-linear penalty function allows smaller penalties for small tardiness but imposes larger penalties for longer tardiness of OT. The larger penalties reduce longer tardiness that may result in missed delivery deadlines at the customer locations. CD model assumes the following key assumptions: 1) IT arrives asynchronously at CD and OT is available at the start of the planning horizon, 2) separate doors are assigned for product unloading (strip door) and loading (stack door) at the CD, 3) transshipment time from a strip door to a stack door is proportional to the distance between the respective doors, 4) preemption is not allowed, 5) unlimited temporary storage is available at the CD, 6) products are interchangeable, and 6) a minimum truck changeover time is imposed at each door. The CD problem is NP-hard, similar to the VRPCD problem. In this study, a two-step solution approach developed by Badyal et al. (2023) is used to solve the CD model. First, a fast constructive heuristic is used to generate the initial solution of the CD model. Second, the Population-Based Simulated Annealing (PBSA) is used to enhance the quality of the solution. The detailed mathematical formulation of the CD model and algorithmic steps of PBSA meta-heuristics can be found in Badyal et al. (2023).

3.2.3 Iterative Information Exchange (IIE)

To accomplish the proposed synchronization of the VRPCD model and CD model, the IIE technique is used. The VRPCD model assumes a fixed duration for product loading and unloading in order to simulate the CD process in the routing problem. The assumed duration of loading and unloading impacts the CD operational time (CD_OP). The

CD_OP is the duration from the arrival of the first IT to the departure of the last OT from the CD. In practice, inaccurate estimation of CD_OP could lead to some, if not all OTs having infeasible routes and increase the tardiness of the system. For the CD model, the arrival times of IT and departure deadlines of OT are crucial information that affects the operational decisions at CD. The CD model could use the accurate arrival and departure times from the VRPCD model. Thus, the aim of IIE protocol is to make the assumed CD_OP from the VRPCD model as close to the actual CD_OP provided by the CD model. To achieve this, the IIE approach utilizes the VRPCD and CD model sequentially and iteratively exchanges information between the VRPCD model and the CD model. The framework for the IIE is illustrated in Figure 2. The following steps are performed in the IIE process.

Step 1: *Initial input to the VRPCD model*

The network data, such as the network transit time, time window, and supplier and customer demand, is the first input used by the VRPCD model. The VRPCD model simulates the operations at CD using the following assumption: 1) CD has sufficient capacity (i.e., number of dock doors, temporary storage, and material handling) for all operations, and 2) a fixed duration is assumed for unloading (u) and loading (u) products at the CD. At the first iteration of the IIE, the VRPCD model assumes (u,l) values equal to (5,5) minutes.

Step 2: *Routing Solution from VRPCD model*

Using the network inputs and assumed values from Step 1, the VRPCD model determines the optimal number of IT and OT, and their respective routes to serve the suppliers and customers. Additionally, the VRPCD model generates an input dataset for the CD model and calculates the CD_OP (CD_OP^{VRPCD}).

Step 3: *Information from the VRPCD model to the CD model*

In this step the VRPCD model provides the following information to the CD model: (i) the number of IT and OT required for pickup and delivery tasks, (ii) arrival times of the IT at CD (iii) departure deadlines of OT, and (ii) number of products carried by each IT, (v) number of products needed by each OT.

Step 4: *Operational Solution from CD model*

The CD model utilizes the information provided by the VRPCD model in Step 3 to determine the following operational decisions: (i) assignment of truck to dock door, (ii) forklift allocation to unload the products from IT, (iii) transfer of products from strip door to stack door, (iv) loading of products to OT, and (v) the earliest departure time of each OT from CD. In addition, the CD model computes the operational time of the CD (CD_OP^{CD}) as an input to the termination criteria.

Step 5: *Check Termination Criteria*

The following two termination criteria are used to check for the final solution. First, how close is the CD operational time computed by the VRPCD model to the CD model? It is calculated from the operational time information from both VRPCD (Step 2) and CD (Step 4). The following equation is used: $closeness = \frac{|CD\_OP^{CD} - CD\_OP^{VRPCD}|}{CD\_OP^{VRPCD}}$. If the closeness value is less than or equal to the specified limit then iteration is terminated. This study used a termination closeness value of 0.05. Second, the maximum number of iterations is used for termination criteria. This study used a maximum iteration of 10 for all experiments.

Step 6: *Information from the CD model to the VRPCD model*

In this step, the input to the VRPCD model is updated for subsequent iterations only if the termination criteria in step 5 is not satisfied. The CD model provides the (u,l) values of each IT and OT to the VRPCD model. The number of IT and OT and the products they are supposed to carry changes in every iteration of the VRPCD model. Therefore, it is not advantageous to use individual (u,l) values for trucks in the VRPCD model. Several statistics could be utilized as (u,l), including the average, median, minimum, and maximum duration. The updated (u, l) values for the VRPCD model are the maximum value of all unloading duration (t_itmax) of IT and the maximum value of all loading duration (t_otmax) of OT. The steps 2 to 4 in IIE are repeated until one of the termination criteria is reached.

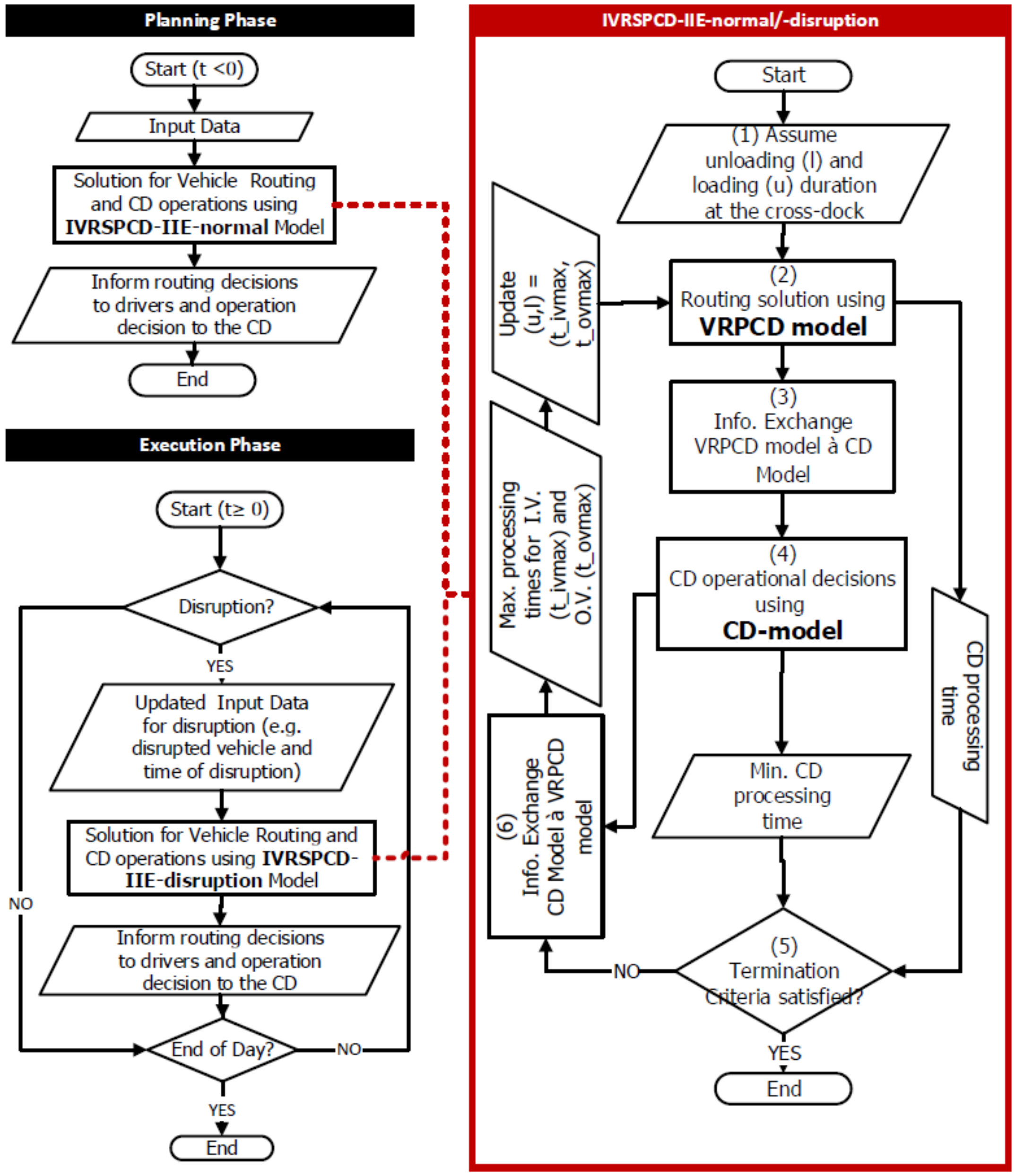


FIGURE 2. Flowchart for planning phase, execution phase, and IVRSPCD-IIE.

The final IIE solution uses the VRPCD model to obtain the IT routes and arrival timings at CD. While the OT routes are determined by the VRPCD model, the CD model specifies when OT departs from CD. As a result, even though the individual models might solve for optimality, the final solution from the SVRSPCD-IIE model is guaranteed to be feasible. In the event of a disruption, the SVRSPCD-IIE solution is extremely useful.

3.3 SVRSPCD-IIE-normal and SVRSPCD-IIE-disruption models

All the operational decisions in the distribution network are taken in two phases: the planning phase and the execution phase. Figure 2 shows the steps of both the planning and execution phases. As shown in Figure 2, the planning phase begins before the start of the day of operation. In this phase, all the routes and operational decisions within the CD are determined using the SVRSPCD-IIE model. In the planning phase, the SVRSPCD-IIE model assumes that the state of the system is in normal condition; meaning there are no interruptions in the network. To indicate that the SVRSPCD-IIE is intended for typical conditions (i.e., without any disruptive events in the network), this model is labeled as the SVRSPCD-IIE-normal. The planning phase ends when all the routing decisions are communicated with the truck drivers and all the operational decisions are known to the CD manager.

The execution phase starts when trucks begin their pre-determined trips at the start of the day ($t \geq 0$) as shown in Figure 2. If the state of the system is normal (i.e., no disruption) during the execution phase, the trucks carry out their trips following the original route plans from the SVRSPCD-IIE-normal. In the execution phase, the distribution network is continuously inspected for any unexpected disruptions. In this study, the breakdown of an IT is considered a disruption event. If any IT encounters a disruption (e.g., breakdown), an increasingly common occurrence, the state of the system is changed from normal condition to disruption condition. The disruption condition makes the original plan infeasible. In this case, a revised SVRSPCD-IIE model is employed to reduce the impact of disruption as much as possible. The revised model is referred to as SVRSPCD-IIE-disruption. The SVRSPCD-IIE-disruption model uses the updated information related to the state of the system. The critical information in disruption includes the identification of the disrupted IT and the start time of IT breakdown. The VRPCD model in the SVRSPCD-IIE-disruption reconstructs the routes of IT and OT using following two recovery strategies: (1) all unserved nodes of the disrupted vehicles are served either by rerouting of enroute vehicle or a new vehicle dispatched from the CD, and (2) a fraction of the unserved nodes served by rerouting of enroute vehicle(s) and the remaining unserved nodes are served by a new vehicle dispatched from the CD. The implementation of these recovery strategies changes the original routes of IT and their arrival times at CD. The CD model takes into account these changes and works together iteratively with the VRPCD model to find the updated solution for the distribution network. The CD model makes several assumptions to incorporate the changes which are as follows: (1) enroute IT whether rerouted or not after the disruption event, will use the original dock doors (2) if additional support IT is used, it will use the strip door assigned to the disabled truck. Similar to the planning phase, these decisions are communicated between the truck drivers and the CD operator to obtain seamless operation.

3.4 Illustrative Example

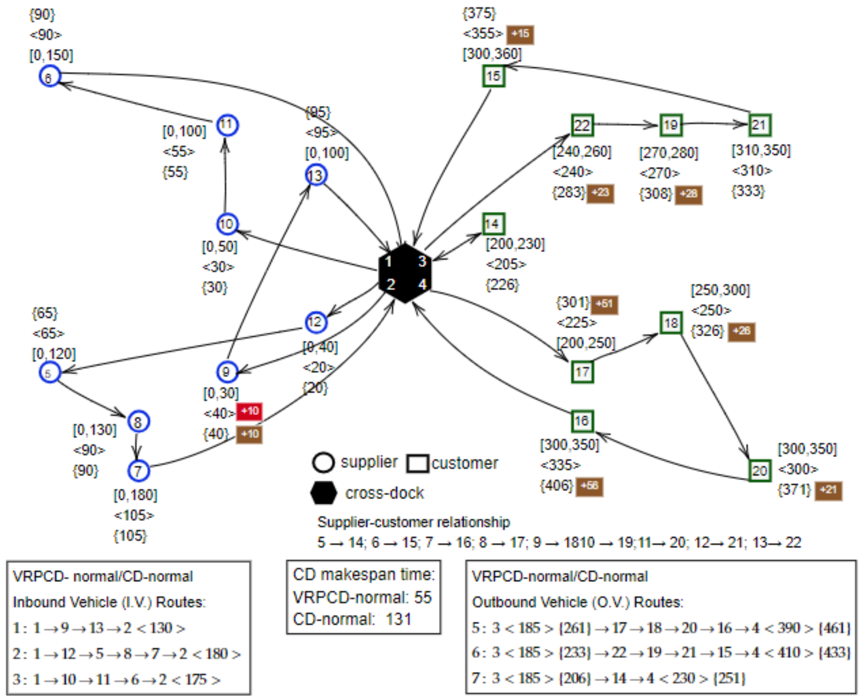
Figure 3 presents a problem instance with 9 suppliers (nodes: 5, 6, 7, 8, 9, 10, 11, 12, 13), 9 customers (nodes: 14, 15, 16, 17, 18, 19, 20, 21, 22), and a cross-dock (nodes: 1, 2, 3, 4). This example illustrates how information exchange between VRPCD-normal and CD-model impacts the vehicle routing and cross-dock operations. The values in square bracket ("[#,#]"), angle bracket ("<#>"), curly brackets ("{#}"), and in parentheses ("(#)") indicates time-window at nodes, arrival time of vehicle at nodes using decisions from VRPCD-normal model, arrival time of vehicle at nodes using decisions from IVRPSPCD-normal model and travel time between nodes, respectively. Figures 3a to 3c show the IIE approach to find the solution for this distribution network.

Figure 3a shows the results of the first iteration of the SVRSPCD-IIE-normal model. In the first step of this iteration, the VRPCD model assumes (u, l) equal to (5, 5). In the second step, the VRPCD model constructs the routes of IT and OT. As shown in Figure 3a three IT (IT-1, IT-2, IT-3) and three OT (OT-1, OT-2, OT-3) serve the suppliers and customers, respectively. The routing plan from the VRPCD model incurred 10 units (node: 9) of tardiness in the system. In the third step, the information on product quantity by each truck, arrival times of ITs, and departure deadlines of OTs were sent to the CD-model. In the fourth step, the CD model updates its operational plan by using the provided information. In the fifth step, the termination criteria are checked. If the termination criteria are not satisfied, the CD model relays back the unloading times of all ITs and the loading time of all OTs. As the final solution of the iteration, the departure times of OTs are updated using the departure times of OT from CD-model, and the tardiness of the system is recalculated. The final solution of the SVRSPCD-IIE-normal model results in late arrival at seven customer nodes (15, 16, 17, 18, 19, 20, 22). The final result from this iteration indicates that the routing cost is 840 units and a total tardiness of 206 units.

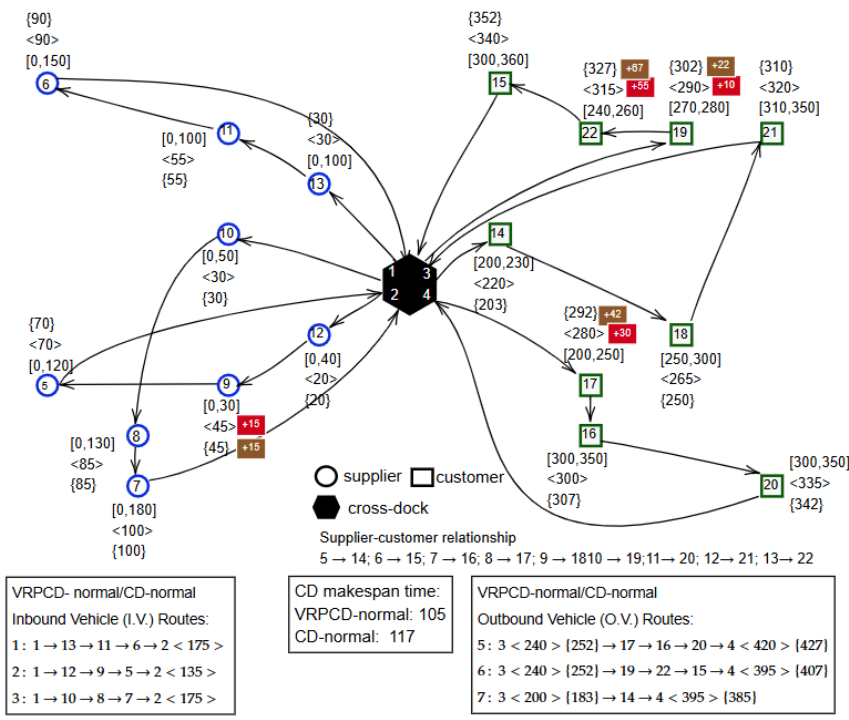
In iteration 2, the VRPCD model updated the values of (u, l) using the information provided by the CD model in iteration 1. In iteration 1, the maximum unloading duration is 36 minutes which is used as the value for u. Similarly, the maximum loading duration is 65 minutes which is used as the value for l. Using these updated values, the SVRSPCD-IIE-normal model determines the solution for iteration 2. The final solution incurs a routing cost of 840 units, tardiness at one supplier location (node 9), and three customer locations (nodes 17, 19, 22) with a total tardiness of 146 units.

	Unloading time	Loading time	Pickup Tardiness	Delivery Tardiness	Pickup cost	Delivery Cost	IT unloading time	OT loading time	Pickup Tardiness	Delivery Tardiness	Pickup cost	Delivery Cost	Objective Value
1	5	5	0	0	498	466	{35, **36**, 21}	{25, 63, **65**}	0	13	498	466	130,951
2	36	65	0	0	596	466	{38, 5, **39**, 11}	{25, 63, **65**}	0	12	596	466	121,050
3	39	65	0	12	556	466	{21, **36**, 35}	{62, 25, **65**}	0	0	556	466	1022
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

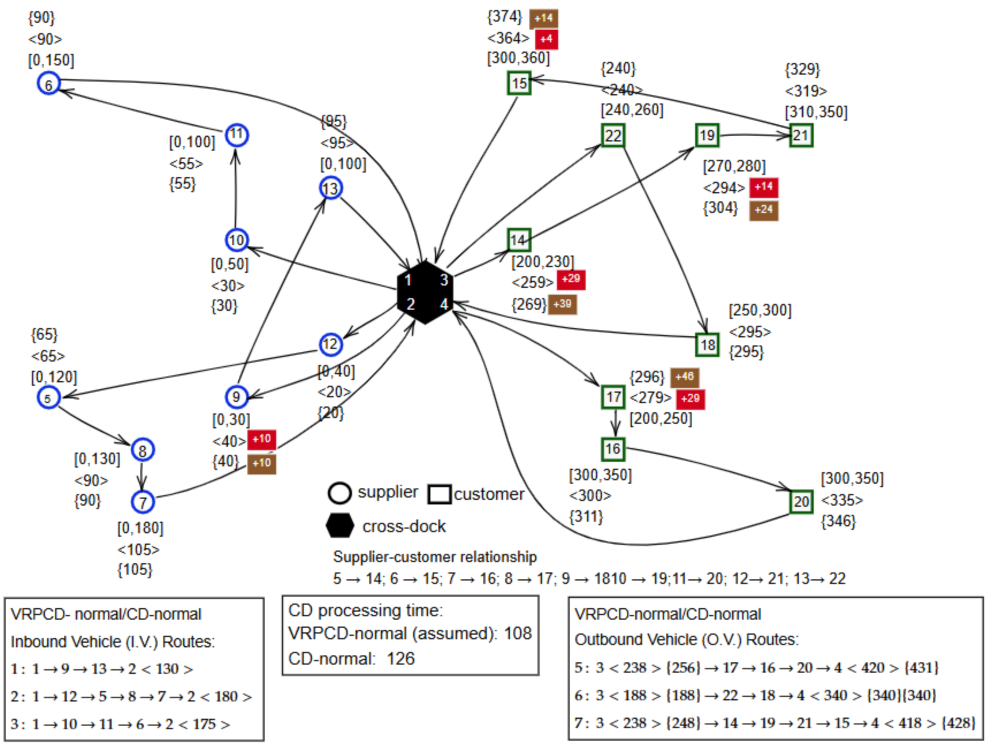
The iteration SVRSPCD-IIE-normal process continues until one of the stopping criteria is met. Among all the iterations, iteration 3 has the minimum objective value and adopted as the best feasible solution for this problem instance.



(a) : *Routing decision from iteration* 01 *from IVRSPCD – normal*



(b) : *Routing decision from iteration* 02 *from IVRSPCD – normal*



(c) : *Routing decision from iteration* 03 *from IVRSPCD – normal*

FIGURE 3. Illustrative example for SVRSPCD-normal model solution.

CHAPTER 4
Numerical Results and Discussion

4.1 Network and Data Description

Figure 4 shows a hypothetical network with suppliers, customers, and a single cross-dock. The cross-dock is located in the middle of the network and represented by nodes {0, 1, 2, 3}. The network consists of nine suppliers represented by nodes {4, 5, 6, 7, 8, 9, 10, 11, 12} and nine customers represented by nodes {13, 14, 15, 16, 17, 18, 19, 20, 21}. The locations of suppliers and customers were randomly selected on a 2D plane that is 120 miles by 120 miles. It was assumed that the location of the CD is in the middle of the network and the coordinate of the CD is (X: 60, Y: 60). The (X, Y) coordinates of suppliers' and customers' locations were obtained randomly from a uniform distribution [0, 60] and [60, 120], respectively.

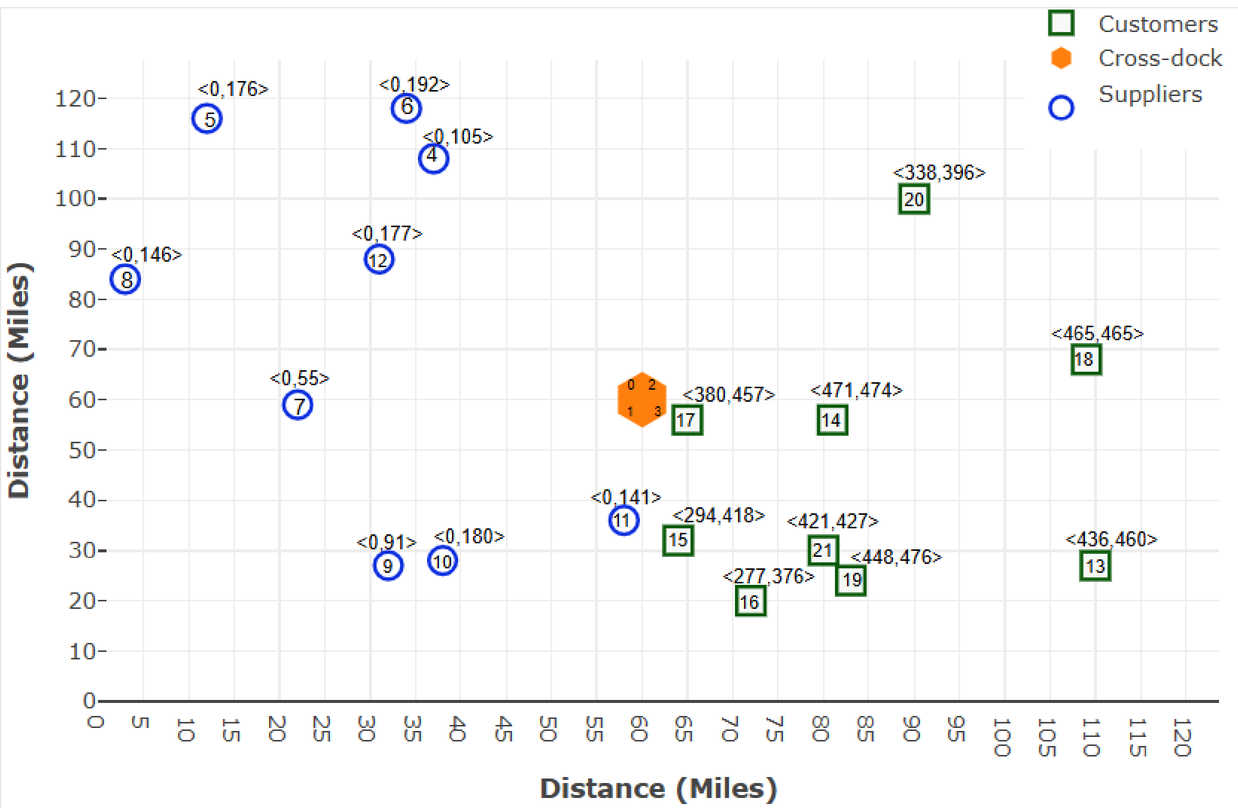


FIGURE 4. Hypothetical network with suppliers, customers, and cross-dock.

The model parameters for the 9-node hypothetical network are as follows. A one-to-one relationship between a supplier and a customer is assumed. The products to be transported from a supplier to a corresponding customer are expressed in the number of pallets and they were randomly generated from a uniform distribution [3, 15]. Both inbound and outbound vehicles have a fixed capacity of 26 pallets and can cover a distance of 60 miles in one hour. The transportation cost to traverse any two nodes in the network is proportional to the travel time between them and the travel time was assumed to be equal to the distance between them. Both the suppliers and customers have time windows. For suppliers, they were generated from a uniform distribution [0, 3.5]. Thus, customer time windows have an upper and lower bound. The lower bound was generated from a uniform distribution [4.5, 8], and the upper bound was generated from a uniform distribution [lower bound, 8]. This study assumed that the planning time horizon, service time at a supplier and customer location, and duration of loading and unloading of pallets at the CD are 16 hours, 5 minutes, and 5 minutes, respectively.

4.2 Experimental Design

Three sets of analyses (Analyses I, II, and III) were performed to evaluate the usefulness of IIE method and the impact of vehicle breakdown on the IVRSPCD network. Analysis I compared the results from the conventional VRPCD model with the proposed IIE method. For analysis I, ten network instances (i.e., random locations of suppliers and customers with the same number of S↔C pair) were generated for the 9-node network.

Analyses II and III assessed how a vehicle breakdown affects the CD, suppliers and customers. Ten network instances were used for the 9-node network to summarize the impact of disruption. For these analyses, two factors were investigated: (i) number of unserved nodes due to vehicle breakdown (referred as N_unserved hereafter), and (ii) the start time of vehicle breakdown and communication delay (referred as T_breakdown hereafter). Three different levels of N_unserved (i.e., 1, 2, 3, 4) and three different levels of T_breakown ("early", "mid", and "late") were examined in the analysis. Therefore, a 3x3 full factorial design of experiments has a total of nine different combinations. The levels of T_breakdown are expressed as a percentage of total pickup process time (i.e., duration from the departure of the first inbound vehicle (t=0) to the arrival of the last inbound vehicle at the CD in the planning phase) and selected based on the time when vehicle breakdown incident occurs. The specified levels of T_breakdown are: "early": 15%, "mid": 30%, and "late": 45%.

To determine the impact of disruption the two-way analysis of variance (ANOVA) was performed on the data. In Analysis II, the makespan time (MK_{cd}) statistic was used to measure the impact of disruption on the CD operation. The makespan time (MK_{cd}) is defined as the time at which the last outbound vehicle leaves the CD. The deviation of the makespan time (MK_{cd}^{dev}) from the IVRSPCD-normal due to vehicle breakdown was computed using Equation (1). The MK_{cd}^{dev} was used as the dependent variable in two-way ANOVA.

$$MK_{CD}^{dev} = MK_{CD}^{IVRSPCD-disruption} - MK_{CD}^{IVRSPCD-normal} \quad (1)$$

For Analysis III, the impact of vehicle breakdown on suppliers and customers was measured using the total delay (TD) metric. The TD is defined as the sum of tardiness at all nodes (or, specified nodes) in the network. The deviation of total delay from IVRPSCD-normal solution TD^{dev} was computed using Equation (2). The TD^{dev} was used as the dependent variable in the two-way ANOVA to measure customer dissatisfaction.

$$TD_{CD}^{dev} = TD^{IVRSPCD-disruption} - TD^{IVRSPCD-normal} \quad (2)$$

4.3 Usefulness of IIE Protocol

Table 1 shows the results of Analysis I. It can be seen that in eight of the ten instances, the IIE protocol lowered the makespans. The difference for one of the two positive cases is negligible. For the other, the increase in makespan was due to the very late breakdown of the inbound vehicle. In six of the ten instances, the IIE protocol significantly lowered the total delay. For the other four cases, there was no difference. Overall, the results of Analysis I demonstrated the effectiveness of the proposed IIE protocol.

TABLE 1. Usefulness of proposed IIE protocol.

ID	Makespan time (minutes)		Total Delay (minutes)		Difference in Makespan (%)		Difference in Total Delay (%)	
	VRPCD	IVRPSCD	VRPCD	IVRPSCD				
9-101	157	139	12	0	-	11.46	-	100.0
9-102	226	227	13	13	+	00.44		0.0
9-103	178	165	11	11	-	07.30		0.0
9-104	348	360	36	22	+	03.45	-	38.89
9-105	317	280	63	22	-	11.67	-	65.08
9-106	292	279	0	0	-	04.45		0.0
9-107	281	271	21	8	-	03.56	-	61.90
9-108	321	300	32	15	-	06.54	-	53.13
9-109	323	284	39	27	-	12.07	-	30.77
9-110	273	260	0	0	-	04.76		0.0

4.4 Impact of Disruption (vehicle breakdown)

The impact of disruption on CD operations and suppliers and customers is assessed via the following hypotheses.

Hypothesis 1. H_0: no interaction between N_unserved and T_breakdown.
Hypothesis 2. H_0: N_unserved has no effect on the dependent variable.
Hypothesis 3. H_0: T_breakdown has no effect on the dependent variable.

Table 2 shows the results of the two-way ANOVA on the effect of N_unserved and T_breakdown on CD operations and suppliers and customers. two-way ANOVA is used to validate Hypotheses 1, 2, and 3 with a significance level of 0.05. Hypothesis 1 tests whether the interaction between N_unserved and T_breakdown is statistically significant. Hypotheses 2 and 3 test whether the main effects of N_unserved and T_breakdown are significant.

TABLE 2. ANOVA results for impact of disruption in the network with cross-dock.

Source	DF	SS	MS	F-statistics	p-value
(a) Impact on CD					
N_unserved	3	8,810	2,937	2.319	0.10
T_breakdown	2	21,147	10,573	8.349	≤ *0.01*
N_unserved × T_breakdown	6	4,312	719	0.567	0.75
Error	57	72,184	1,266	-	-
(b) Impact on suppliers					
N_unserved	3	5,583	1,861	3.248	*0.03*
T_breakdown	2	24,032	12,016	20.976	≤ *0.01*
N_unserved × T_breakdown	6	4,739	4,739	1.379	0.24
Error	57	36,652	32,652	-	-
(c) Impact on customers					
N_unserved	3	94,141	31,380	8.939	≤ *0.01*
T_breakdown	2	145,298	72,649	20.674	≤ *0.01*
N_unserved × T_breakdown	6	56,550	9,425	2.685	*0.02*
Error	57	200,109	3,511	-	-
(d) Impact on suppliers and customers					
N_unserved	3	134,128	44,709	9.355	≤ *0.01*
T_breakdown	2	287,454	143,727	30.073	≤ *0.01*
N_unserved × T_breakdown	6	89,434	17,906	3.119	*0.01*
Error	57	272,420	4,779	-	-

N_unserved: Number of unserved nodes; T_breakdown: Start Time of Vehicle Breakdown and Comm. Delay; DF: degrees of freedom; SS: Sum of squares; MS: Mean SS

4.4.1 Impact on Cross-Dock Operation

Table 2a presents the results of a two-way ANOVA on the effects of *N_unserved* and *T_breakdown* on makespan at the cross-dock. The ANOVA results in Table 2a indicate that the main effect is statistically significant ($F(3, 57) = 8.349$, $p \leqslant 0.05$) only for *T_breakdown*. However, the interaction effect between *N_unserved and T_breakdown* is not statistically significant ($F(6, 57) = 0.567$, $p > 0.05$). This result suggests that the change in mean deviation of makespan time is related to the T_breakdown only.

Figure 5 shows the main effect plot of the impact of the *T_breakdown* on the deviation of makespan. It can be seen that the mean deviation of makespan time increases as the T_breakdown increases. This result suggests that as the vehicle breakdown occurs later in the pickup time horizon, the CD operation takes longer to complete its operations (i.e., longer makespan).

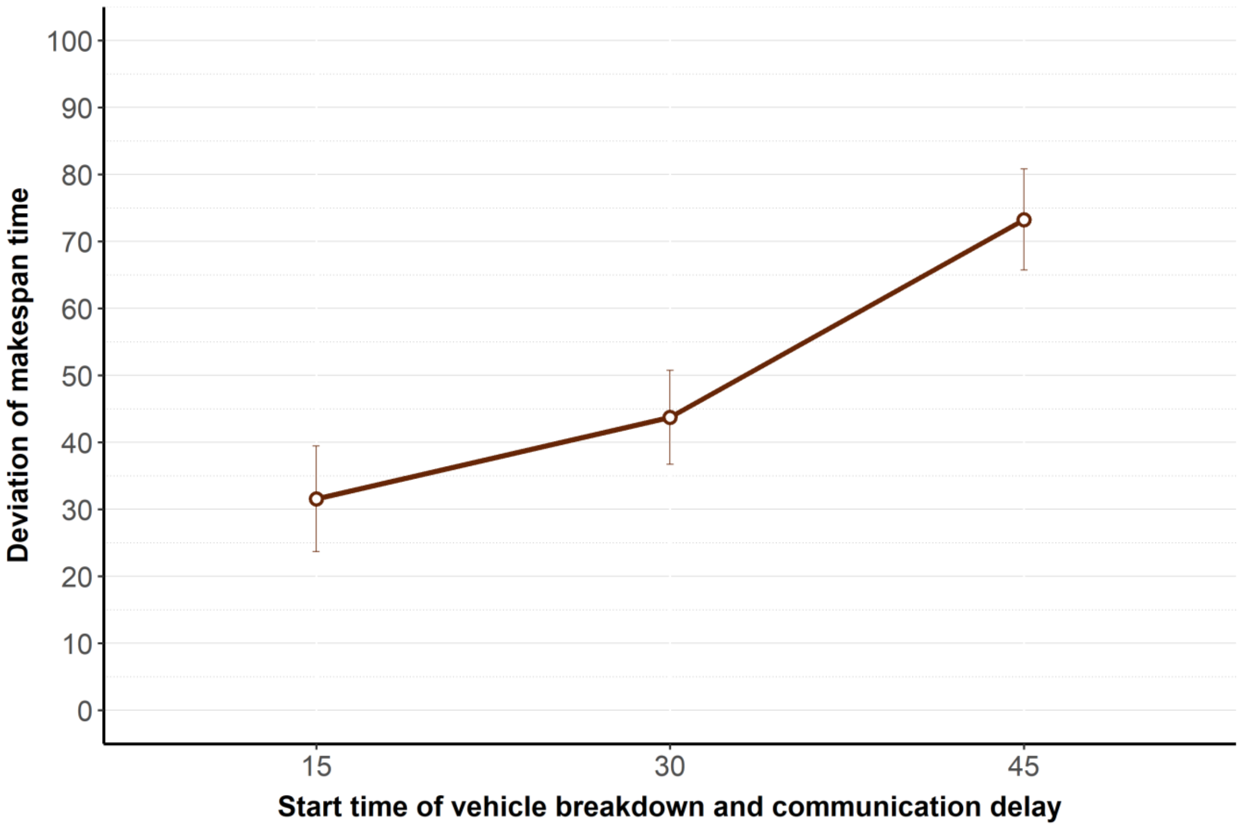


FIGURE 5 Main effect of start time of vehicle breakdown and communication delay on deviation of makespan time for cross-dock operation.

4.4.2 Impact on Suppliers and Customers

4.4.2.1 Impact of service delay on suppliers

Table 2b presents the results of a two-way ANOVA on the effects of *N_unserved* and *T_breakdown* on total delay for the suppliers. The ANOVA results in Table 2b indicate the main effects *N_unserved* ($F(3,57) = 3.25$, $p \leqslant 0.05$) and T_breakdown ($F(2,57) = 20.98$, $p \leqslant 0.05$) are statistically significant. However, the interaction effect between *N_unserved* and *T_breakdown* is not statistically significant ($F(6, 57) = 1.38$, $p > 0.05$).

Figures 6a and 6b show the main effect plots of the impact of *N_unserved* and *T_breakdown* on the deviation of total service delay for the suppliers, respectively. Figure 6a shows that the mean deviation of total service delay increases as *N_unserved* increases. Additionally, the rate of increase in deviation of total service delay is higher when the number of unserved nodes increases from 3 to 4 compared to when the number of unserved nodes increases from 1 to 2. Figure 6b reveals a similar trend for deviation of total service delay as in *T_breakdown* increases. In this case, a steady rate of increase in deviation of total service delay is observed.

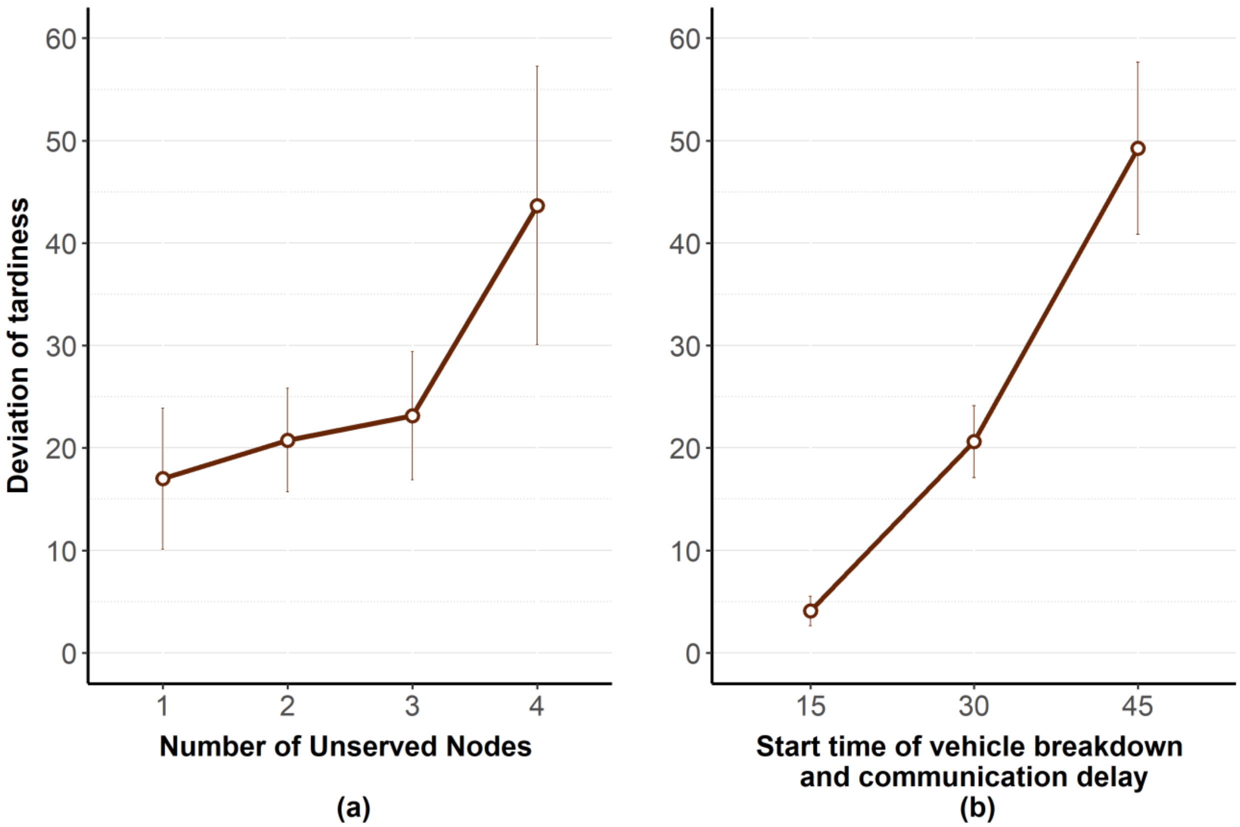


FIGURE 6 Main effect of (a) start time of vehicle breakdown and communication delay and (b) number of unserved nodes on deviation of tardiness for suppliers.

4.4.2.2 Impact of service delay on customers

Table 2c presents the results of a two-way ANOVA on the effects of N_unserved and T_breakdown on total service delay for customers. The ANOVA results in Table 2c indicate the main effects N_unserved ($F(3, 175) = 8.94$, $p < 0.05$) and T_breakdown ($F(2, 175) = 20.67$, $p < 0.05$) are statistically significant. Additionally, the interaction effect between *N_unserved* and *T_breakdown* is statistically significant ($F(4, 175) = 2.69$, $p < 0.05$). Therefore, for any level of N_unserved, the change in mean service delay for customers is related to the level of T_breakdown.

Figure 7 presents the interaction plot of the impact of N_unserved and T_breakdown on total service delay for customers. It can be seen that increases in N_unserved and T_breakdown increases the total service delay for customers. For any level of N_unserved, the mean total service delay does not change significantly and as close to zero for disruption occurring at 15% (i.e., early). Figure 7 also reveals that the increase in T_breakdown from 15% (i.e., early) to 45% (i.e., late) for any number of N_unserved increases the mean total tardiness. These results indicate that early (i.e., 15%; “early”) breakdown of the inbound vehicles with any number of nodes on its route does not impact the service delay in the delivery process.

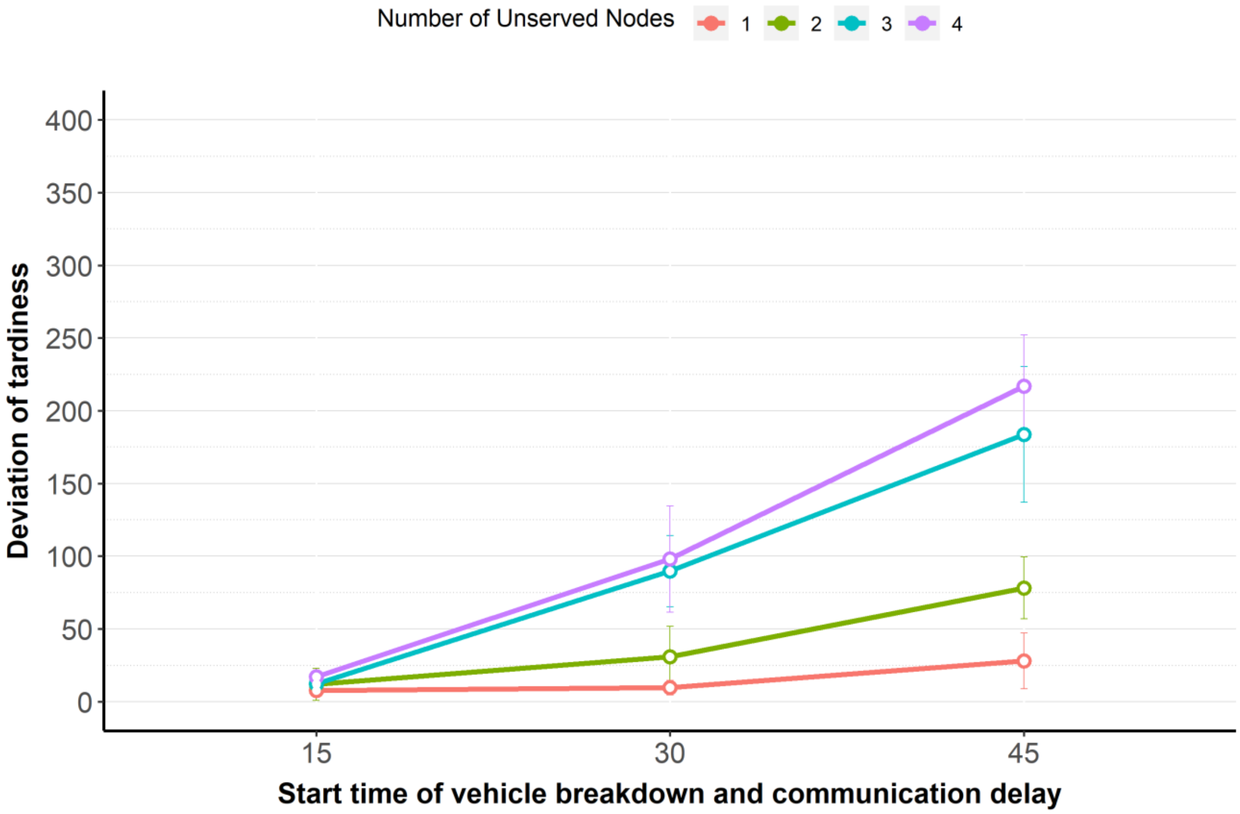


FIGURE 7 Interaction plot (ANOVA analysis) for impact of tardiness for the customers.

4.4.2.3 Impact of service delay on suppliers and customers

Table 2d presents the results of a two-way ANOVA on the effects of N_unserved and T_breakdown on total service delay for suppliers and customers. The ANOVA results in Table 2d indicate the main effects of N_unserved ($F(3, 175) = 9.36$, $p < 0.05$) and T_breakdown ($F(2, 175) = 30.07$, $p < 0.05$) are statistically significant. Additionally, the interaction effect between N_unserved and T_breakdown is statistically significant ($F(4, 175) = 3.12$, $p < 0.05$). As a result, the change in mean service delay for any level of N_unserved is related to the level of T_breakdown.

Figure 8 presents the interaction plot of the impact N_unserved and T_breakdown on the total service delay for suppliers and customers. It can be seen that an increase in N_unserved and T_breakdown will increase the mean total service delay which is similar to the impact on customers. These results suggest that an early breakdown of an inbound vehicle with fewer number of unserved nodes on its route, as opposed to a late breakdown of an inbound vehicle with a higher number of unserved nodes, is associated with a smaller service delay.

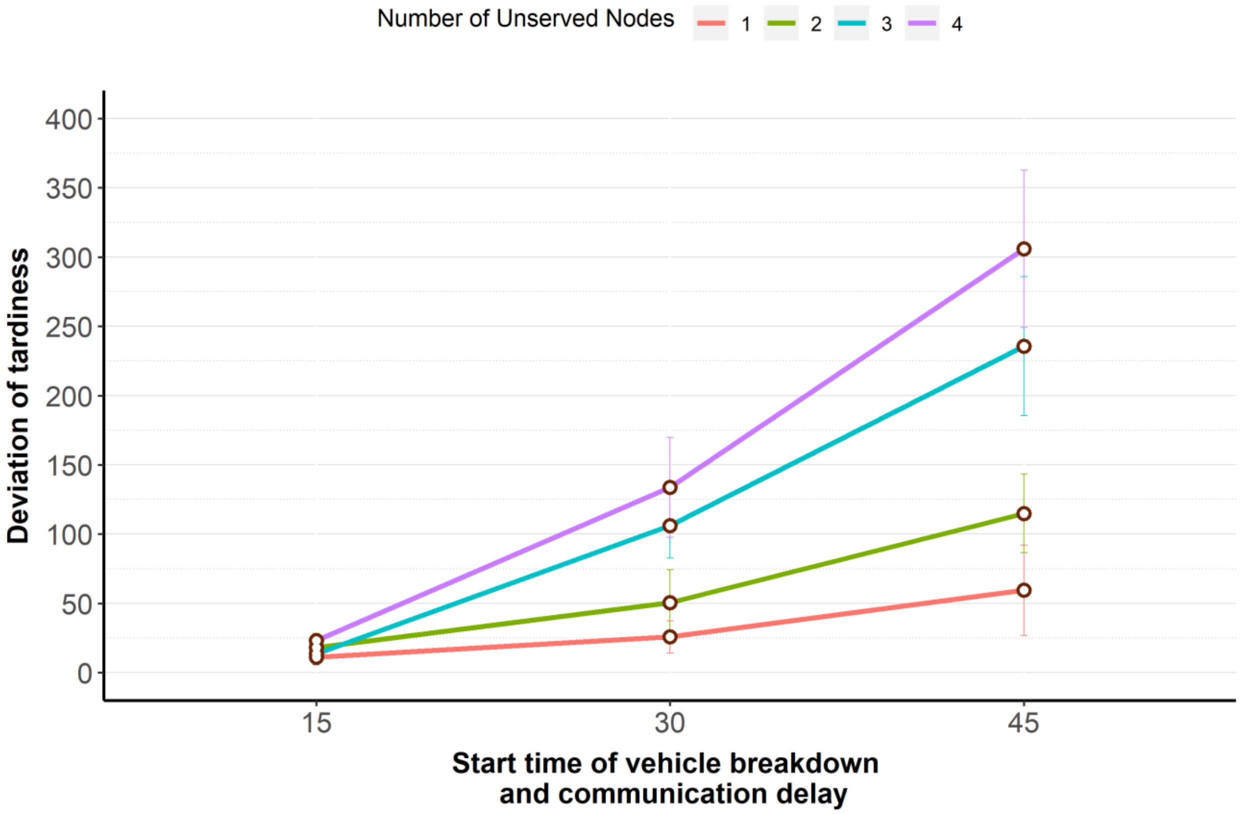


FIGURE 8 Interaction plot (ANOVA analysis) for impact of disruption on suppliers and customers.

Chapter 5

Summary and Conclusions

Disruptions in freight logistics are not uncommon in practice and have widespread negative impacts on the system, including late vehicle arrivals to suppliers, CD, and customers. The objective of this study was to minimize such disruptions by developing a protocol to synchronize the decisions between truck dispatchers, drivers, and the cross-dock operator. The developed reactive recovery system consists of two main components: an integrated vehicle routing and scheduling model for normal conditions (IVRSPCD-normal) and a similar model for disruption conditions (IVRSPCD-disruption). To demonstrate the effectiveness of the developed IVRSPCD models, numerical experiments were performed on a hypothetical network. Results from the numerical experiments showed that the proposed IIE protocol is effective in lowering the makespan and total delay in the event of a disruption. The CD makespan was primarily affected by the start time of the vehicle breakdown and communication delay. The delay at the supplier locations was affected by both the number of unserved nodes due to vehicle breakdown and the start time of the vehicle breakdown and communication delay. The same was true for the delay at the customer locations; however, there is an additional interaction effect between the two variables. The same finding applied to the case where the delay for both suppliers and customers is considered.

The contributions of this study to the VRPCD literature are:

- Including disruptions in IVRSPCD: While disruptions due to vehicle breakdown have been studied for VRP and VRPCD, to the best of the authors' knowledge, this study is the first to consider a vehicle breakdown for the IVRSPCD.

- Developing communication scheme for IVRSPCD: While previous studies developed a combined mathematical model for IVRSPCD, this study considers vehicle routing and scheduling at CD problem separately for routing planner and CD. Instead of a combined mathematical model, synchronization is performed using information exchange.

- Developing insights into the impact of disruptions: This is the first study to quantify the impact of disruption due to vehicle breakdown on service quality and CD operations in IVRSPD.

The findings from this study should be applied with the recognition of its limitations: (1) the experiments of this study is limited in scope in terms of the network size, (2) the IIE framework assumes distributed computing systems to implement the mathematical model, and and (3) the logistic service provider and CD manager have data sharing agreement. The conclusions of effectiveness of IIE framework and impact of disruption drawn from this study are strictly pertain to the evaluation of small-scale network. To make the findings more generalizable, future study should include numerical experiments for larger and more varied network instances.

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