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Handling disruptions in a network with cross-docking

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Handling disruptions in a network with cross-docking

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***Abstract* — Cross-docking (CD) is a commonly used technique to consolidate freight for more efficient delivery to customers; CD is continuing to see increased use by companies. Synchronization of inbound and outbound freight is clearly critical to operations and so is having the cross-dock able to support the freight flow with available doors and material handling equipment. The latter is particularly important when there is a disruption in the inbound freight. One delayed truck can impact several outbound trucks. A methodology is proposed to address explicitly both the scheduling of trucks and material handling within the CD. Two models are proposed – one for routing inbound and outbound trucks and the other to schedule the cross-dock. Results from each model when run separately are presented as well as results from when the two models are run iteratively.**

Keywords — cross-dock, material handling, disruptions

I. INTRODUCTION

A cross-dock terminal is a transshipment facility between shippers and customers used to consolidate freight by destination. Cross-docks increase truck utilization by avoiding multiple shipments to a single destination on partially filled trucks. In this research, it is assumed that inbound trucks collect freight from suppliers and deliver it to the cross-dock. There, the freight is redirected to outbound trucks for delivery to customers. Cross-docks are designed for and operated with high freight velocity so any inventory in a cross-dock is only held for a very short time. Hence, the functional requirements of a cross-dock are: 1) unload inbound trailers, 2) sort freight by destination, 3) transfer freight to temporary storage if necessary, and 4) load outbound trailers. This research focuses on a network with a cross-dock with separate inbound and outbound vehicles as depicted in Figure 1.

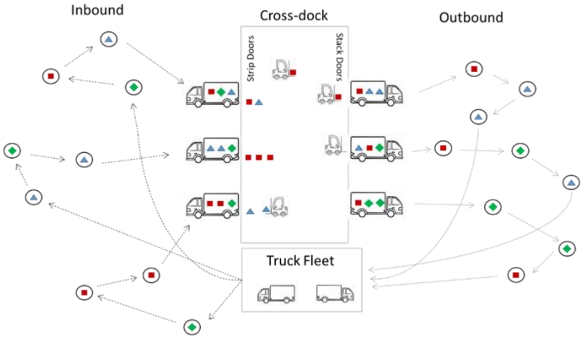

Fig 1. Logistics network with a cross-dock

For a cross-dock to function well, inbound and outbound trailer scheduling must be synchronized [1] and a feasible schedule for the forklifts must be available to support the arrival and departure of the inbound and outbound trucks. Poor synchronization or a lack of adequate material handling can lead to delayed outbound trailer departures, unavailability of dock doors to accommodate arrived inbound trailers, and increased storage that creates congestion and delayed freight transfers.

To manage the integrated scheduling, a plan is developed for each day that includes the routes for trucks picking up freight, routes for trucks delivering freight, and a schedule for the forklifts. A cost-based objective function is frequently used to minimize one or more important operating characteristics such as late deliveries, the makespan at the cross-dock, the number of trucks utilized, and/or the total distance traveled by trucks. Since mathematical programming models developed for this problem are NP hard, heuristics of various types have been used to find solutions. These are often quite effective when things go according to the plan; however, disruptions are quite common in practice. As such, the decision-maker is confronted with a dilemma. On one hand, they could continue executing the original plan, but this will likely result in a diminished or total lack of synchronization at the cross-dock. Alternatively, a new plan could be developed that reroutes trucks already picking up freight and/or dispatch new trucks from the cross-dock. Outbound routes can also be adjusted, all the while a feasible forklift schedule and a feasible dock door schedule must be maintained. This research theme emanates from real-world situations.

There are two important practical operating issues that, to the best of our knowledge, do not appear in the literature. The first is the need to have a feasible schedule for the material handling devices (e.g., forklifts) within the cross-dock to support inbound and outbound truck schedules. The second is to accommodate the disruption (i.e., delay) of inbound trucks in such a way that outbound deliveries are disrupted as little as possible and that the forklifts can support the new arrival and departure schedules. This paper discusses ongoing research addressing these two issues and preliminary results.

II. BRIEF LITERATURE OVERVIEW

A. *Modeling cross-docks*

Cross-docking is a practical but complex operation that has received significant attention from researchers from a variety of perspectives. Many researchers restricted the cross-dock to a single stack door where freight is loaded on outbound trucks and a single strip door where freight is unloaded from inbound trucks. They identified realistic scenarios that are inherently complex, developed a model that is NP-hard, and proposed a variety of heuristics to find decent solutions for reasonably sized problems. For example, Yu et al. [2] developed multiple iterative heuristics based on inbound trailer and outbound trailer selection strategies. Vahdani et al. [3] assumed no temporary storage is available but allowed trailers to be partially loaded/unloaded at one door and finish later at another. Arabani et al. [4] explored using a just-in-time philosophy to schedule trailers and compared three metaheuristics for finding solutions: genetic algorithms (GA), particle swarm optimization (PSO), and differential evolution (DE).

The literature most relevant to this research focuses on the cross-docking problem in a post-distribution setting with interchangeable products. This means that an outbound trailer's demand for a product can be satisfied by any inbound trailer with available supply for that product. The literature on this type of problem, however, is limited. Liao et al. [5] focused exclusively on sequencing inbound trailers to minimize total weighted tardiness and compared six meta-heuristics: simulated annealing (SA), tabu search (TS), ant colony optimization, DE, and two hybrid DE's. Tootkaleh et al. [6] assumed no product interchangeability under normal circumstances but allowed it if inbound trucks were delayed. Assadi et al. [7] scheduled inbound trailers just-in-time but with scattered inbound and outbound trailer arrival times using DE and population-based SA (PBSA) to find solutions.

There are two literature review papers on cross-docking. The first is by Agustina et al. [8]which reviews mathematical modeling approaches for cross-dock planning at operational, tactical, and strategic levels. The second one is by Torbali and Alpan [9] which reviews robust and real-time models to address contemporary cross-docking challenges.

B. Routing inbound and outbound trucks

Scheduling inbound and outbound trucks to a cross-dock is often formulated as a vehicle routing problem (VRP). Lee et al. (2006) were the first, to our knowledge, to combine the VRP with a cross-dock (VRPCD). The goal was to determine the optimal inbound and outbound routes to and from the cross-dock, so that freight are moved from suppliers to customers efficiently. This initial work assumed synchronous product arrivals to facilitate consolidation and used tabu search to find the routes. Subsequently, different features such as asynchronous arrivals, time windows, limited vehicle capacities, and emissions have been modeled. The seminal manuscript by Wen et al. [10] spawned a significant amount of research subsequently (e.g., [11] and [12]).

Different approximation methods have been used to find solutions for VRPCD, including simulated annealing [13], genetic algorithms [14], local search heuristics [15], and column generation [16], to name a few.

III. METHODOLOGY

To address the VRPCD network depicted in Fig. 1, two models are developed to work together iteratively. One model takes supplier and customer requirements and creates a *plan* that specifies routes for inbound trucks and when they should arrive at the cross-dock and routes for outbound trucks and when they must depart from the cross-dock to avoid or minimize late deliveries to customers and reduce transportation costs. The other model determines the plan for the forklifts within the cross-dock to move the freight given inbound truck arrival times and outbound truck departure times from the first model. If no such plan is possible, the inbound and outbound arrival times are adjusted to find a suitable plan for the forklifts.

A. Cross-dock model

In this research, we assumed that the cross-dock has multiple dock doors, outbound trailer tardiness is tolerable when they are small but non-consequential when they are large, and arriving products are interchangeable. There is no *a priori* assignment of products from a specific inbound trailer to a specific outbound trailer. A mathematical model was developed to determine the arrival times and departure times of inbound trailers while explicitly considering material handling (i.e., plan for forklifts). The objective function minimizes the tardiness of outbound trailer departures and the makespan. Tardiness is modeled by a convex nonlinear function with small penalties for small delays to reflect the real possibility that vehicle rerouting can mitigate small delays; however, larger penalties are assessed for longer delays because these delays will likely result in missed deadlines for some deliveries. This problem is known to be NP-hard so heuristics are needed and justified for larger, realistic-sized problems. In this study, a new PBSA meta-heuristic that is based on the general strategy proposed by Yu et al. [2] was developed.

B. Vehicle routing/rerouting model

At the beginning of the planning horizon, a set of suppliers with freight to be shipped and a set of customers needing the freight to be delivered within predefined time windows is assumed to be known. A fleet of homogenous vehicles is used to execute the pickup and delivery tasks. Inbound trucks leave the cross-dock and visit the suppliers to pick up goods before returning to the cross-dock. At the cross-dock, incoming products are unloaded, sorted, consolidated, and reloaded on outbound vehicles that depart from the cross-dock to deliver goods to the customers after the loading is complete. It is assumed that the cross-dock has sufficient capacity (i.e., dock doors, temporary storage, and material handling) to move the freight. No split shipments are allowed. Further, both suppliers and customers have time windows for pick-ups and deliveries. Some of these time-window constraints are "soft" which means they can be violated but there is a cost penalty and others are "hard" which means they must be met. The model determines the routes of the inbound and outbound vehicles with the objective of minimizing the cost that consists of the penalty for late deliveries and the transportation cost that is based on the total distance traveled. It is assumed that the planning horizon is a 16-hour day. Routes for all trucks are constructed before the day begins using the developed model based on the work of Yu et al. [17] and Nikolopoulou et al. [18]. This model is labeled VRPCD-normal to denote that it is designed for normal/typical conditions. Some unique features of this model not found in the literature are asynchronous arrivals of inbound and outbound trucks, a more comprehensive cost of transportation that reflects a closed system, and a many-to-many relationship between inbound and outbound trucks at the cross-dock.

After planning is complete, the execution phase begins. Each vehicle has its route at the start of the day, and if there are no disruptions on any route of an inbound truck, the original route plan is followed. When an inbound truck encounters a disruption (e.g., wreck), an increasingly common occurrence, a second model is engaged to mitigate the impact of the disruption as much as possible. This model, labeled VRPCD-disrupted, utilizes three recovery strategies: 1) all unserved nodes of the disrupted vehicle are served by enroute vehicles through rerouting, 2) all unserved nodes of the disrupted vehicle are served by a new vehicle(s) dispatched from the cross-dock, and 3) a fraction of the unserved nodes is served by an enroute vehicle(s) through rerouting and the rest are served by new vehicle(s) dispatched from the cross-dock. To model these options, several assumptions are made to reflect the following: 1) All unaffected inbound trucks will use their original routes and dock doors, 2) if an additional truck is required and is available, it will depart from the cross-dock and return to the cross-dock, 3) if an additional truck is dispatched, it will use the strip door assigned to the failed vehicle. Enroute vehicles, re-routed or not, will use the strip doors that were determined by the VRPCD-normal model.

Since both of these VRP models are NP-hard, algorithms must be used to find approximate solutions. In this research, the Golden Ball Algorithm was adapted because it was found to be highly effective in solving the VRP with backhauls and time windows [19].

IV. RESULTS

This section presents some numerical results that were obtained by running the cross-dock model and VRPCD routing/rerouting models independently and by running them together. For the cross-dock model, it was a result born from the simple question of whether the model should be based on a fixed or mixed door operating strategy. This led to an interesting finding that is still under exploration. The vehicle routing/rerouting models seem to constantly provide somewhat unexpected results and insights for different scenarios that require further investigation. Connecting these two models posed new challenges with a significant one being what information need to be exchanged between the two models to find a reasonable solution. The numerical results follow.

A. *Cross-dock model*

As described previously, the cross-dock model produces sequences of inbound truck arrivals and outbound truck departures that explicitly considers forklift scheduling. Several heuristics have been developed including the proposed PBSA algorithm to find these sequences and the forklift assignments. For example, if a fixed door strategy (i.e., strip and stack doors are designated *a priori*) is used, then the cross-dock model produces the results presented in the form of Gantt charts in Figs. 2 and 3.

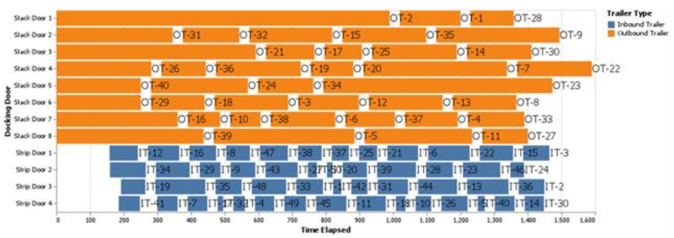

Fig 2. Truck schedule at cross-dock for strip and stack doors

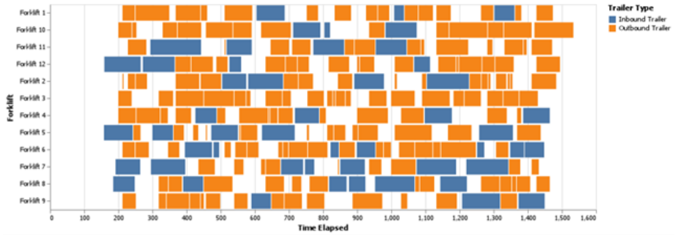

Fig 3. Forklift schedule

In Fig. 2, the eight horizontal strips at the top of the chart are the stack doors and the lower four strips are the strip doors as indicated by the y-axis labels. The orange and blue rectangles are the different inbound and outbound trucks that the model assigned to each door. For example, outbound truck 2 (OT-2) shown in the topmost strip indicates that it is scheduled to arrive at stack door 1 from time 0 to approximately 1200.. Similarly, inbound truck 12 (IT-12) is scheduled to arrive at strip door 1 at approximately time 150. Fig. 3 shows how the 12 forklifts are scheduled. Forklifts are identified on the y-axis and each rectangle denotes the type of move that the forklift will perform (either to unload the inbound trucks or load the outbound trucks). The trucks associated with stack and strip doors are not included in Fig. 3 to avoid cluttering the Gantt Chart.

One interesting preliminary result was discovered when a comparison was made of cross-dock performance using a fixed door and mixed door strategy (i.e., the model can assign any door to be a strip or stack) for the same inbound and outbound demands. The model assumes that a fixed amount of time is required for unloading an inbound truck and another fixed amount of time to deliver freight from any strip door to any stack door for loading outbound trucks. Recall that the objective function seek to minimize the tardiness of outbound trailer departures and the makespan. In this experiment, products are assigned to trucks so supply is controlled to be exactly equal to the demand. Truck arrival times and departure deadlines are generated randomly within ranges. The range of arrival times is always earlier than the departure deadline but there is some overlap. Fig. 4 and Table 1 show the results for 50 randomly generated scenarios when the loading and unloading times are equal.

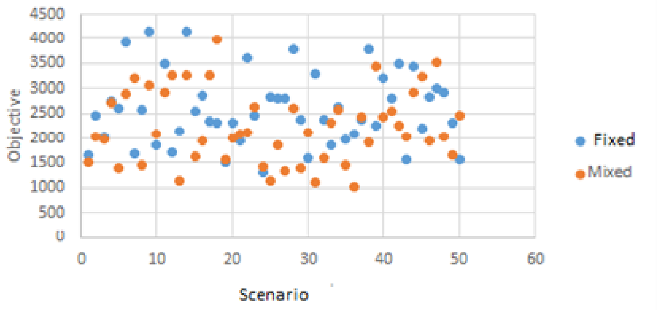

Fig 4. Model performance with equal loading and unloading times

TABLE I. EQUAL LOADING AND UNLOADING TIMES

	Fixed doors	Mixed doors
Mean	2573	2219
Std Dev	729	732
Minimum	1312	1033
Maximum	4157	3982

Close observation indicates that the mixed doors is better for each scenario but most differences between these are very small. Frankly, we expected a must more pronounced difference. In fact, the two strategies are not statistically different in aggregate. On the other hand, when the unloading time is twice the loading time, the results are quite different as shown in Fig. 5 and Table 2. Note that these scenarios are different from those above, hence, the reason for differences in objective function values.

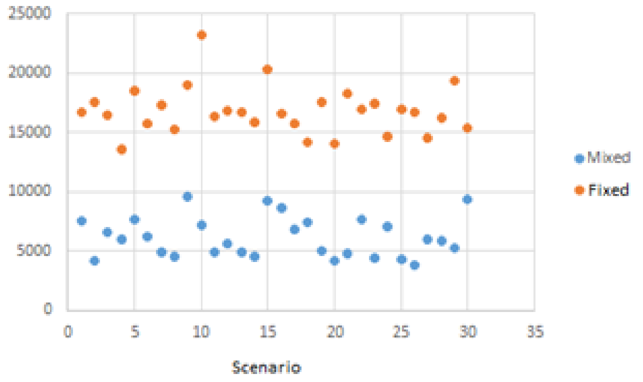

Fig 5. Model performance when loading time is twice the unloading time

TABLE II. LOADING TIME TWICE THE UNLOADING TIME

	Fixed doors	Mixed doors
Mean	16808	6158
Std Dev	1991	1694
Minimum	13581	3783
Maximum	23229	9642

The unequal loading an unloading times produced results that were expected. Understanding the reason why equal times for loading and unloading creates little difference between using a fixed or mixed doors strategy is still under investigation.

B. *Vehicle routing/rerouting models*

To explore the vehicle routing/rerouting models, a specific scenario was adopted that consists of predefined pick-up nodes (suppliers) and delivery nodes (customers) as well. The location of each node is known as well as the quantity and type of product to be picked up or delivered. Time window constraints are also known. Before the day begins, the VRPCD-normal model finds the best routes for each truck to service the suppliers and customer. These optimal routes are depicted in Fig. 6. Note that inbound trucks are denoted as IV and outbound trucks as OV. The best solution found by the Golden Ball Algorithm has a 10-minute delay at one of the pick-up locations shown in red as +10.

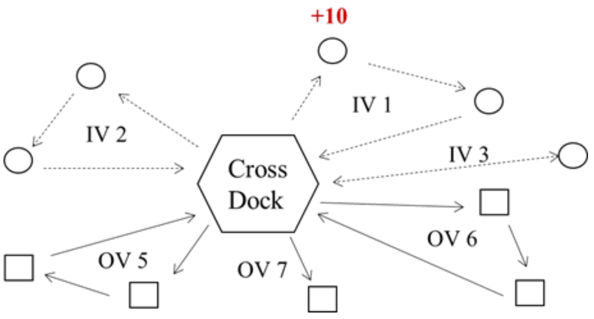

Fig 6. Initial routes

A disruption occurs as the inbound vehicles are enroute to their first destination that incapacitates IV 2. VRPCD-disrupted is then engaged to find the solution that is least impactful on suppliers and customers. Recall, VRPCD-disrupted considered rerouting currently enroute vehicles as well as adding new vehicles. The best updated routes are illustrated in Fig. 7.

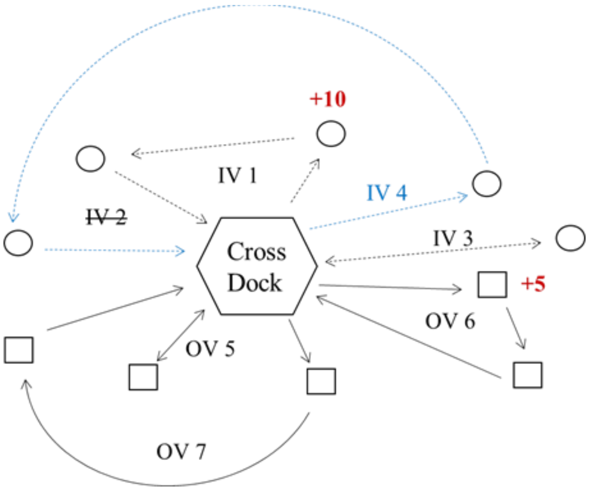

Fig 7. Routes after disruption

The VRPCD-disrupted model provides a schedule that yields the least impact to IV 1, OV 5 and OV 7, by adding an new inbound truck, IV 4, shown in blue in Fig 7. The overall impact is quite small because only one customer has a delayed arrival of 5 minutes despite this rather significant disruption.

C. *Combined models*

The two vehicle routing models and the cross-dock model can be used together to address planning and disruptions in a network. The iterative use of these models is now outlined assuming the planning horizon is a day. It is assumed that the requirements of the suppliers and customers (i.e., locations, product type(s) and amount(s) to be picked up/delivered, and time windows) are known.

- Before the day's activities begin, the VRP-normal model is solved to determine the routes of the pick-up and delivery vehicles that meet supplier and customer demands with minimum penalty associated with tardiness plus transportation cost. The arrival times of the inbound trucks and the departure times of the outbound trucks are passed to the cross-dock model. Note that this information defines the makespan at the cross-dock.
- The cross-dock model is solved with the input from the VRPCD-normal model. If the material handling can support the proposed truck arrivals and departures, the day's routes are set. If not, then the cross-dock model is solved for an alternate set of departure times for outbound vehicles and those are passed back to the VRPCD-normal model.
- This process repeats until a feasible solution is found or a termination criterion is met like no improvement in the solution for a fixed number of iterations or the difference between the makespans of the two models is within a predetermined gap.

When a disruption is encountered during the day, the same process is used *except* the VRPCD-disruption model is used rather than the VRPCD-normal model.

To illustrate how the process works, consider a network with five pick-up nodes (5,6,7,8,9) and five delivery nodes (10,11,12,13,14,15). Table III shows the results of the first iteration.

TABLE III. FIVE NODE EXAMPLE - INTIAL ITERATION

	Pick-up trucks			**Delivery trucks**		
	1	2	3	1	2	3
	VRPCD-normal					
Nodes served	7,8	9,5	6	10,11	13,12	14
Arrive/depart cross-dock	150	130	165	170	155	135
	Cross-dock model					
Arrive/depart	150	130	165	207	214	202

Notice that the material handling in the cross-dock cannot support the proposed departure times of the three delivery trucks given the arrival time of the inbound trucks so this is not considered a reasonable solution. Hence, information on delivery truck departures that can be supported by material handling with the given arrivals are returned to VRPCD-disrupted for a second iteration. The objective function value in this initial iteration is 100,690. Table IV shows the results of the second iteration.

TABLE IV. FIVE NODE EXAMPLE – SECOND TERATION

	Pick-up trucks				**Delivery trucks**		
	1	2	3	4	1	2	3
	VRPCD-normal						
Nodes served	5	6	8	9,7	14,12	13	10,11
Arrive/depart cross-dock	125	165	125	150	188	163	203
	Cross-dock model						
Arrive/depart	125	165	125	150	234	167	207

VRPCD-disrupted now adds an inbound truck to assist with the pick-ups. This creates a rerouting of the three delivery trucks that delays the required departure time of each. Unfortunately, the material handling still cannot support this proposed schedule although the differences are much smaller. The objective function value has increased to 100,830.

The third iteration keeps the same four pick-up trucks but adds two delivery trucks to the network. The results are indicated in Table V.

TABLE V. FIVE NODE EXAMPLE – THIRD ITERATION

	Delivery trucks				
	1	2	3	4	5
	VRPCD-normal				
Nodes served	11	14	10	12	13
Arrive/depart cross-dock	215	200	175	200	175
	Cross-dock model				
Arrive/depart	230	202	202	167	167

Even with each delivery node served by a single truck, all required departure times cannot be satisfied. At this point, either this schedule would be adopted and customer whose delivery will be delayed notified or another adjustment would be made to relieve the bottleneck like adding forklifts or inbound trucks.

Applying these models to a larger network of 13 suppliers and 13 customers shows a similar result as indicated in Table VI.

TABLE VI. THIRTEEN NODE EXAMPLE

	Delivery trucks				
	1	2	3	4	4a
	Iteration 1				
Arrive/depart VRPCD	180	160	180	160	
Arrive/depart CD model	236	223	223	188	
	Iteration 2				
Arrive/depart VRPCD	220	245	245	180	200
Arrive/depart	236	211	163	188	169

CD model					

There are two important items to note. The first is that both of the VRPCD models can use a single truck for more than one route in a day. Here, truck 4 is sent out on a short delivery to two nearby customers before returning to the cross-dock for a second trip. The reason the truck was not sent on a single route is because the inbound freight needed for one of the customers on the second route was not available in time to meet the delivery deadline of one of the first two customers. The second item to notice how is much improvement is made in just one iteration of the models. So, even though this methodology is not easy and completing an iteration could take a bit of time and effort, rather significant improvements can be realized in a few iterations. We imagine that having a good schedule that matches material handling capacity with freight transfer demands and having a forklift schedule to support this at the start the day would be quite beneficial. Being able to reroute after a disruption in such a way to cause minimum impact on suppliers and customers, and with the confidence that it can be executed because the freight movements within the cross-dock has been coordinated, would provide a tremendous advantage and reason to approach real situations like this using the proposed methodology.

From a practical viewpoint, it is clear that the actual travel times could vary from those used in the deterministic models. Hence, if conservative estimates of travel time are utilized, it is quite possible that even if a solution to the model suggests departure time requirements are missed by 5% or 10%, the arrival times of the outbound trucks could actually occur on schedule.

V. CONCLUSIONS

This research has developed a methodology for handing disruptions in a network that includes a cross-dock by linking two models. One model determines the routes for inbound and outbound trucks to the cross-dock while the other schedules the cross-dock doors and the forklifts within the cross-dock to move the freight.

An interesting result found by using the cross-dock model alone is that there is very little difference in efficiency between using a fixed and mixed doors strategy when the time to unload and load trailers are equal. However, if the times are unequal then the mixed doors model is more efficient.

The VRP models were shown to be very effective in scheduling inbound and outbound truck arrivals to minimize an objective function consisting of a penalty for late deliveries to customers and the transportation cost. The Golden Ball Algorithm has again proved to find very good solutions and is amenable to adjustments that are required for constraints or pathological conditions found in some numerical examples.

The methodology that iteratively uses these two models shows promise in creating the initial routes for inbound and outbound trucks at the beginning of a day and subsequently rerouting of enroute vehicles and adding inbound trucks in the event of a disruption to yield arrivals and departures that can be supported by the cross-dock material handling.

Research continues on all three of these research themes based on the positive results thus far and the potential practical value of the work.

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