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A Practical Collaborative Material Handling Strategy for Cross-docks

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***Abstract*— The current operational paradigm at less-than-truckload (LTL) cross-dock industry (*i.e.*, dedicated strategy) is to assign one material handler (MH) per inbound trailer. As a consequence, each loaded trip performed by a MH to move a load from the assigned inbound door to the loads' corresponding outbound door is followed by an identical empty trip to return to the inbound door. This paper introduces the monomaniacal strategy as a practical rule-based material handling collaborative strategy for LTLs designed to minimize the total empty travel. In the monomaniacal strategy, after delivering a load to an outbound door, MHs travel counterclockwise to the next available inbound trailer. Several mathematical formulations are presented to compare the proposed strategy to the current operational paradigm in terms of the total material handling distance required to unload all trailers. It is concluded that the proposed monomaniacal strategy outperforms the dedicated strategy without considering that loads have (LIFO) precedence constraints by an average of 17.45% and is within 25.59% of the theoretical optimal solution that requires a centralized decision support system. Other experimental results suggest that the optimal inbound door assignment for the monomaniacal strategy coincided with the optimal inbound door assignment for the dedicated strategy and that the optimal solution for the monomaniacal strategy is robust with respect to the sequence of the loads within inbound trailers. The main benefit of the monomaniacal strategy is that it can be readily implemented without requiring changing the door assignment or incurring in any investments.**

***Keywords*—cross-dock, operational paradigm, shared strategy, material handling pooling**

I. Introduction

It is customary in the less-than-truckload (LTL) cross-dock industry is that, upon arrival, truck drivers become material handlers (MHs) for the cross-dock (XD). An operational paradigm in LTL XDs is that the MHs are responsible for unloading the contents of the inbound trailers they bring to the XD. Therefore, each loaded trip performed by a MH from an inbound door to an outbound door is followed by an identical empty trip to return to the inbound trailer. We refer to this operational paradigm as the *dedicated strategy*. Clearly, half of the total distance traveled in cross-docks that use the dedicated strategy is empty travel. This means that there is incredible potential to improve the total distance traveled in a XD simply by challenging the dedicated strategy operational paradigm. Reducing the total material handling distance to unload trailers will reduce the completion time of the trailers, which is one of the main metrics for efficiency in XDs.

Interestingly, the currently used dedicated strategy operational paradigm in LTL XDs is not explicitly acknowledged in the existing literature review papers [1-4 of IISE]. However, all published papers related to dock door assignment problem (implicitly or explicitly) acknowledge the operational paradigm of dedicating material handlers to inbound trailers (*i.e.*, the dedicated strategy). The dock door assignment problem seeks to find the trailer-to-door assignment that minimizes the travel distance or time (*e.g.*, [5-10 in IISE]) to move all loads from the inbound trailers to their respective outbound trailers. Except for Santiago-Montaño and Carlo [11], all other XD dock door assignment papers where material handlers are considered optimize a metric where travel distance is represented as a function of the loaded travel distance – mainly twice the loaded travel distance.

Carlo and Santiago-Montaño [12] and Santiago-Montaño and Carlo [11] were the first to identify the dedicated strategy as an operational paradigm in XDs. These papers proposed a *shared strategy* where after delivering a load the MHs may select a different inbound trailer from the one they brought in to the cross-dock. In particular, these papers studied what we will call the *optimal shared strategy* where the routing of the MHs are simultaneously optimized. Carlo and Santiago-Montaño [12] present a mathematical formulation to find the MHs route that minimize the total travel distance (and makespan) under a shared strategy, given the inbound and outbound dock door assignments. It was found that for a XD with a door assignment optimized for the dedicated strategy, the optimal shared strategy yields an average percent improvement of over 24% on the total distance traveled and 49% in terms of the makespan considering three different flow profiles in a 16 door XD. Santiago-Montaño and Carlo [11] extend the work of [12] by incorporating the inbound dock door assignment as a decision when optimizing the MHs route under a shared strategy. Their main managerial insight reported in the paper is that the optimal inbound door assignment for the dedicated strategy is also optimal for their optimal shared strategy. The way the optimal shared strategy is conceived in these papers has two main limitations: 1) that it would require a centralized decision support tool that informs the MHs which load to retrieve next, and 2) that it does not consider that loads must be retrieved from the trailers according to a last-in-first-out (LIFO) policy. In this study we directly extend the work of [12] in two ways: 1) by proposing an easily implementable version of the shared strategy (*i.e.*, the monomaniacal strategy), and 2) by incorporating LIFO when retrieving the loads. The importance of this work is that it proposes a new implementable material handling operational strategy for XDs that could significantly reduce the logistics costs.

The remainder of this paper is organized as follows. Section 2 describes the monomaniacal strategy and explains how to obtain a lower bound for the total travel time under the monomaniacal strategy using the shared strategy mathematical formulation from [12]. Section 3 presents an alternative model to optimize the total travel time for the shared strategy and extends it to incorporate LIFO. Section 4 presents some numerical experiments. Lastly, the conclusions are presented in Section 5.

II. Monomaniacal Strategy

The monomaniacal strategy is a new rule-based strategy that forces each MH to travel counterclockwise to the next available inbound trailer after delivering each load. (The counterclockwise direction of the monomaniacal strategy is selected for driving-safety purposes assuming that driving occurs on the right lane.) Unlike the optimal shared strategy from [11] and [12], the decision making under the monomaniacal strategy is decentralized, which makes it easily implementable in all XDs. Figure 1 presents an example contrasting the MH routing for dedicated (left) and monomaniacal (right) strategies. The total loaded distances for both strategies are identical, as the inbound-to-outbound flows are the same.

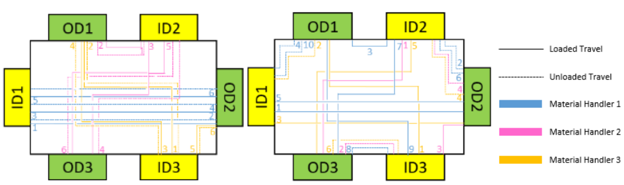

Fig. 1. Sample dedicated (left) and monomaniacal (right) unloading process

Implementing a shared strategy might face some resistance by the MHs. Some of the challenges in adapting a shared strategy may include union or haulers' rules and regulations, and convincing MHs that the policy is fair and beneficial from the perspective of the MHs and the inbound trailers. We understand that the monomaniacal strategy, if proven to outperform the current dedicated strategy, should be implementable in the majority of XDs with minimal effort.

The following modeling assumptions are made in this paper:

- inbound and outbound door assignments are given;
- unloading sequence in inbound trailers (LIFO) is given;
- material handling equipment (MHE) used in the XD can carry one load per trip and are readily available;
- the number of MHE equals the number of inbound trailers;
- the number of inbound trailers equals the number of inbound doors;
- each MH starts in a different inbound door and ends in the same door they started;
- all travel distances are known and measured rectilinearly;
- acceleration/deceleration and congestion are not considered;
- there is no staging at the XD.

With the exception of the second assumption (*i.e.*, LIFO), these modeling assumptions are identical as the ones in [12]. In fact, the mathematical formulation from [12] may also be used to obtain the optimal MHs route under the monomaniacal strategy if we disregard the LIFO assumption. The only modification required to that formulation is to use the monomaniacal distances (*i.e.*, distance between each outbound door and the closest inbound door in the clockwise direction) to populate the unloaded travel distance d_{ji}^{u} in the model. Hence, the formulation from [12] may be used as a lower bound for our problem (which considers LIFO). It is worth recognizing that the optimal shared strategy in [11] and [12] was not meant to be a practical strategy that can be readily implemented in XDs, but as a way to cost-out the dedicated strategy operational paradigm.

In the next section we present an alternative formulation to the one in [12] and extend it to consider LIFO within trailers. The formulations in [12] works at the trailer level, which facilitates the extension to optimize the inbound door assignment as in [11]. On the other hand, the formulation proposed here works at the load (typically pallet) level, which can be easily extended to incorporate the precedence constraints based on LIFO.

III. Mathematical Formulation

Consider the following basic notation for the formulation assuming that the material handling unit (loads) are pallets.

<u>Sets</u>:

$\mathcal{P}$ set of pallets, indexed over $p, q \in \{1, .., P\}$ where the last I pallets correspond to dummy pallets, each assigned as the last pallet to be retrieved in each of the I inbound doors

$\mathcal{P}_f$ set of first retrievable pallets (*i.e.*, the first pallet that can be retrieved from each trailer), $\mathcal{P}_f \subset \mathcal{P}$, $|\mathcal{P}_f| = I$.

$\mathcal{P}_d$ set of dummy pallets, $\mathcal{P}_d \subset \mathcal{P}$, $|\mathcal{P}_d| = I$. These pallets are included as the last pallet in each trailer.

$\mathcal{S}$ set of move sequences (*i.e.*, the movement index for each MH), indexed over $s \in \{1, .., S\}$

$\mathcal{K}$ set of material handlers, $k \in \{1, .., K\}$, where $K \equiv I$ (the number of inbound doors) per modelling assumption 4. Furthermore, MH k is to start unloading the first pallet in trailer k.

<u>Parameters</u>:

M = a very large constant

d_{pq} travel distance (or time) incurred to serve pallet $p \in \{1,..,P\}$ and move to retrieve pallet $q \in \{1,..,P\}$ next. This distance represents the loaded travel required to move pallet p from the inbound door to which the inbound trailer containing pallet p is assigned, plus the empty travel from the outbound door to which pallet p is delivered to the inbound door from which pallet q will be retrieved. It is assumed that $d_{pq} \equiv M \quad \forall\, p \in \mathcal{P}_d, q \in \mathcal{P} \setminus \mathcal{P}_d$, $d_{pp} \equiv 0 \; \forall\, p \in \mathcal{P}_d$, $d_{pp} \equiv M \; \forall\, p \in \mathcal{P} \setminus \mathcal{P}_d$

a_{pq} precedence constraint matrix with value 1 if p precedes q, 0 otherwise. Note that precedence constraints occur within trailers

n = number of physical (non-dummy) pallets per inbound trailer ($n \equiv (P - I)/I$)

Decision Variables:

$z_{p,q}^{k,s}$ binary variable equal to 1 if the k^{th} material hander moves pallet $q \in \{1,..,P\}$ immediately after moving pallet $p \in \{1,..,P\}$ as his s^{th} movement.

u_p the start time for transporting pallet $p \in \{1,..,P\}$

$$min\; z^{shared} = min\{\textstyle\sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{P}}\sum_{k\in\mathcal{K}}\sum_{s\in S} d_{pq} z_{p,q}^{k,s}\} \quad (1)$$

s.t.

$$\textstyle\sum_{q\in\mathcal{P}\setminus\mathcal{P}_f}\sum_{k\in K}\sum_{s\in\mathcal{S}} z_{p,q}^{k,s} = 1 \quad \forall\, p \in \mathcal{P} \setminus \mathcal{P}_d \quad (2)$$

$$\textstyle\sum_{p\in\mathcal{P}\setminus\mathcal{P}_d}\sum_{k\in K}\sum_{s\in\mathcal{S}} z_{p,q}^{k,s} = 1 \quad \forall\, q \in \mathcal{P} \setminus (\mathcal{P}_f \cup \mathcal{P}_d) \quad (3)$$

$$\textstyle\sum_{p\in\mathcal{P}\setminus\mathcal{P}_d} Z_{p,q}^{k,s} = \sum_{p\in\mathcal{P}\setminus\mathcal{P}_f} z_{q,p}^{k,s+1} \quad \forall q \in \mathcal{P} \setminus (\mathcal{P}_f \cup \mathcal{P}_d), \; k \in \mathcal{K}, s < S \quad (4)$$

$$\textstyle\sum_{p\in\mathcal{P}} Z_{p,q}^{k,s} = z_{q,q}^{k,s+1} \quad \forall q \in \mathcal{P}_d, k \in \mathcal{K}, s < S \quad (5)$$

$$\textstyle\sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{P}\setminus\mathcal{P}_f} z_{p,q}^{k,s} = 1 \quad \forall\, k \in \mathcal{K}, s \in \mathcal{S} \quad (6)$$

$$\textstyle\sum_{q\in\mathcal{P}\setminus\mathcal{P}_f} z_{n*k-n+1,q}^{k,1} = 1 \quad \forall\, k \in \mathcal{K} \quad (7)$$

$$\textstyle\sum_{p\in\mathcal{P}} z_{p,n*K+k}^{k,S} = 1 \quad \forall\, k \in \mathcal{K} \quad (8)$$

$$z_{p,q}^{k,s} \in \{0,1\} \quad \forall\, p \in \mathcal{P}, q \in \mathcal{P}, k \in \mathcal{K}, s \in \mathcal{S} \quad (9)$$

$$U_{n*k-n+1} = 0 \quad \forall\, k \in \mathcal{K} \quad (10)$$

$$U_q \geq U_p + d_{pq} - M(1 - \sum_{k\in K}\sum_{s\in\mathcal{S}} z_{p,q}^{k,s}) \quad \forall\, p \in \mathcal{P} \setminus \mathcal{P}_d, q \in \mathcal{P} \setminus \mathcal{P}_f \quad (11)$$

$$U_q \geq U_p - M(1 - a_{pq}) \quad \forall\, p \in \mathcal{P} \setminus \mathcal{P}_d, q \in \mathcal{P} \setminus \mathcal{P}_f \quad (12)$$

$$\textstyle\sum_{k\in K}\sum_{s\in\mathcal{S}} z_{q,p}^{k,s} \leq (1 - a_{pq}) \quad \forall\, p \in \mathcal{P} \setminus \mathcal{P}_d, q \in \mathcal{P} \setminus \mathcal{P}_f \quad (13)$$

$$U_p \geq 0 \quad \forall\, p \in \mathcal{P} \quad (14)$$

The objective function in Eq. (1) minimizes the total parts travel. It is observed that in this paper the terms distance and time are used interchangeably which implies that we assume, without loss of generality, a one distance unit per time unit constant travel velocity. Constraint sets (2) and (3) ensure that all pallets are unloaded. Constraint sets (4) and (5) maintain flow conservation between move sequences. The former is designed for non-dummy pallets, whereas the latter is specifically designed for dummy pallets. Since the dummy pallets are considered sinks, once they are reached the MH cannot move on to another pallet. Constraint set (6) forces each MH to perform exactly move per sequence. Constraint sets (7) and (8) respectively force each MH start and finish in the same inbound door they started. Constraint set (9) establishes our main decision variable as binary. Constraint set (10) ensures that the initial values of the start time for the first pallet in each trailer is zero. Constraint set (11) defines the start time for transporting each pallet as the start time of the previous pallet plus the respective travel distance. Constraint set (12) ensures that the start times honor the precedence constraints and constraint set (13) does the same for the decision variable. Lastly, in (14) the start time decision variables are delimited. Notice that the sub-problem composed of constraint sets (1-9) is an alternative to the optimal shared strategy formulation in [12], which also serves as a lower bound for our problem. Also, the proposed formulation may be easily adjusted for the minimize makespan objective using a similar strategy as in [12].

IV. Experimental Results

In this section we compare the traditional, optimal shared, and monomaniacal strategies with and without precedence constraints in terms of the total distance traveled. The mathematical models are coded and solved using LINGO 11.0. The solution from the dedicated strategy does not require solving a mathematical model as the routes for the MHs are implied and independent of the load sequence per the dedicated strategy. A 12 door rectangular XD with 4 doors on the longer side and 2 on the shorter side is used to compare the three strategies. It is assumed that half of the doors are inbound and the rest are outbound. The distances between doors from [9] are used when constructing the XD. The distance matrices for the optimal shared and monomaniacal are computed for each; for optimal shared we find the minimal rectilinear travel between all doors and for the monomaniacal we use the counterclockwise travel patterns. In the initial experiments we assume that each inbound trailer has *n*=10 non-dummy loads (pallets) that need to be cross-docked. When generating the inbound trailer flow composition it is assumed that each inbound trailers interacts with between 3 and 6 outbound trailers. Ten instances are randomly generated.

The simulated annealing heuristic (SA) and parameters from [9] is used to determine a good outbound door assignment considering the ten instances. The SA evaluates outbound door assignments by solving a linear assignment problem (LAP) for the inbound trailer-to-door assignment for each night. The ten replicates for each flow composition are used as nightly flows when solving the SA. Therefore, each instance has the same outbound door assignment obtained with the SA, and for each problem instance the optimal inbound door assignment was obtained with a LAP. Hence, the inbound and outbound door assignments used for each instance are heuristically optimized for the dedicated strategy. The resulting door assignment alternates between inbound and outbound doors – the alternating doors template from [10].

A. Comparison of strategies without LIFO assumption

The formulation from [10], which disregards LIFO within inbound trailers, was used to compare the three strategies. Table 1 summarizes the results. In this table the optimal solution for the dedicated, optimal shared, and monomaniacal are presented in columns 2-4, and their respective percent differences are presented in the subsequent columns (*e.g.*, z_{opt}/z_{mono} −1 in column 4) . Figure 2 presents the resulting objective function values pictorially.

TABLE I. EXPERIMENTAL RESULTS WITHOUT LIFO ASSUMPTION

Inst.	z_{dedi}	z_{opt}^{shared}	z_{mono}^{shared}	Percent Differences		
				mono-opt	mono-dedi	opt-dedi
1	260	208	248	19.23%	-4.62%	-20.00%
2	286	218	234	7.34%	-18.18%	-23.78%
3	334	244	268	9.84%	-19.76%	-26.95%
4	294	226	248	9.73%	-15.65%	-23.13%
5	314	234	262	11.97%	-16.56%	-25.48%
6	298	226	258	14.16%	-13.42%	-24.16%
7	334	234	256	9.40%	-23.35%	-29.94%
8	342	242	246	1.65%	-28.07%	-29.24%
9	354	254	282	11.02%	-20.34%	-28.25%
10	288	216	246	13.89%	-14.58%	-25.00%
				10.82%	**-17.45%**	**-25.59%**

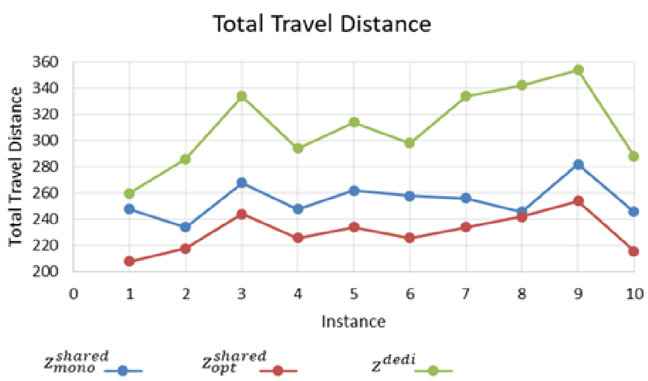

Fig. 2. Function Values Without LIFO Assumption

It can be observed from Table 1 that the proposed monomaniacal strategy outperformed the dedicated strategy in all instances by an average of 17.45% in terms of total material handling distance. This reduction in total travel comes from an average reduction of 34.91% in the unloaded travel distances. On the other hand, as expected, the optimal shared strategy outperformed the monomaniacal strategy by an average of 10.82%. Lastly, the optimal shared outperformed the dedicated strategy by 25.59% similar to what was reported in [11] and [12]. A pairwise Tukey test with a 95% confidence level confirms that the three operational strategies are statistically different.

B. Optimizing inbound door assignment without LIFO

The formulation from [11], which incorporates the inbound trailer-to-inbound door decisions to the formulation in [12] was used to find the optimal inbound door assignment for the ten instances under the monomaniacal strategy. Similar to the formulation in [12], the formulation in [11] disregards the LIFO reality within inbound trailers. The same outbound door assignment used in the previous experiments was used for these experiments. It was found that for all ten instances the optimal inbound door assignment for the dedicated, which is also optimal for the optimal shared according to [11], is also optimal for the monomaniacal strategy. This result suggests that managers can continue to use the same inbound door assignment as before when implementing the monomaniacal strategy.

Although it was not explored empirically, it is hypothesized that the optimal door assignment for the monomaniacal strategy follows an alternating doors template as coined by [11] (*i.e.*, one that alternates between inbound and outbound doors). Door assignments with two consecutive inbound doors under the monomaniacal strategy will always strip the first door in the counterclockwise direction, before starting the other door. Clearly, if a second trailer replaces the first counterclockwise trailer, then this trailer will also be unloaded before its downstream neighbor. Therefore, the monomaniacal strategy is not recommended for XDs with more inbound doors that outbound doors. On the other hand, in practice XDs have more outbound doors (destinations) than inbound doors [9].

C. Effects of LIFO in monomaniacal strategy

In this set of experiments we use the mathematical model in section 3 to determine the effect of the LIFO assumption in the monomaniacal strategy. Given the complexity of the formulation we created a smaller instance with 6 doors (3 inbound doors) following the same strategy for generating instances as before. The new instance has 6 (non-dummy) loads per trailer, but the loads may only retrieved following the LIFO policy. Twelve replicates were generated by changing the precedence constraints within inbound trailers. The replicates can be considered as different permutations of the loads within trailers. For simplicity, we kept forced the first load in each trailer to be the same in all replicated. Notice that each replicate has exactly the same loads (*i.e.*, origin/destination), and only the unloading sequence was changed.

Interestingly all replicates found the same objective function value, which coincided with the objective function value obtained when no precedence constraints were enforced. Therefore, our results suggest that the monomaniacal strategy seems to be robust to the sequence of loads within trailers. This result is expected to hold as long as the inbound trailers are scattered throughout the XD.

V. CONCLUSIONS

This study proposes a practical collaborative strategy to minimize the empty travel distances (or times) in less-than-truckload cross-docks (XDs) called the monomaniacal strategy. The proposed strategy is classified as a shared operational strategy where material handlers (MHs) collaborate to unload all inbound trailers. In the monomaniacal strategy each MH travels counterclockwise upon delivering loads to outbound trailers. Internally generated experimental instances were used to compare the performance of the proposed strategy with the traditional (dedicated) strategy – where each MH unloads a trailer – and the optimal strategy that minimizes the total travel distance. It is concluded that the proposed monomaniacal strategy outperforms the dedicated strategy without considering that loads have (LIFO) precedence constraints by an average of 17.45% and is within 25.59% of the theoretical optimal solution that requires a centralized decision support system. A second experiment suggests that the optimal inbound door assignment for the monomaniacal strategy coincided with the optimal inbound door assignment for the dedicated strategy. Lastly, it is concluded that the optimal solution for the monomaniacal strategy is robust with respect to the sequence of the loads within inbound trailers.

The importance of this work is that it proposes a new implementable material handling operational strategy for XDs that could significantly reduce the logistics costs without requiring any investment. Analytical models are used to quantify the potential benefit of implementing the monomaniacal strategy in XDs around the world. Future work should simulate the proposed strategy to understand the effects of congestion, understand the fairness of the policy, and test different versions of the policy.

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