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Freight Sequencing to Improve Hub Operations in the Less-Than-Truckload Freight Transportation Industry

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Abstract

In less-than-truckload freight transportation, hub operations affect the service levels that carriers are able to provide their customers. This paper focuses on improving the efficiency of hub operations by reducing freight handling time and cost. Specifically, the freight sequencing problem (FSP) is investigated to determine the freight unloading and loading sequence that minimizes the time for dock workers to transfer shipments from origin trailers to destination trailers. The FSP is modeled as a Rural Postman Problem (RPP) and three algorithms are compared: trailer-at-a-time, nearest neighbor, and balance-and-connect. Using five industrial data sets, the results demonstrate the effectiveness, advantages, and disadvantages of the approaches.

1 Introduction

Freight transportation plays a key role in the national and global economy. In 2008, logistics costs in the United State increased to $1.18 trillion (or 9.5% of nominal GDP), with 62% of the costs related to freight transportation [1]. In freight transportation, three types of carriers handle different classes of freight: parcel, truckload, and less-than-truckload (LTL). LTL freight is often too large to be transported through a parcel system but not large enough to justify dedicating an entire truck to the shipment. LTL carriers often route freight through a network of service center and hubs. At a hub, freight from various service centers is unloaded and consolidated onto trailers traveling to the appropriate destination service center.

The LTL industry is one of the most competitive industries in the United States [2][3]. To remain competitive, LTL carriers strive to improve customer service and reduce the costs associated with transportation and handling. Service levels and costs in the LTL industry greatly influence customer satisfaction and have a major effect on revenues.

This research strives to reduce delivery time and costs to improve service levels for hub operations.

In LTL networks, shipments are typically transported from origin service centers to the appropriate hub location each afternoon. During the evening, trailers that have arrived at the hub (referred to as origin trailers) are unloaded. Departing trailers (referred to as destination trailers) are loaded with appropriate shipments from the service centers. After a destination trailer is loaded, the trailer is dispatched to another hub or a service center, where the freight is distributed to the customer.

A hub manager determines the assignment of origin trailers and destination trailers to the dock doors at the hub. After the origin trailers and destination trailers are assigned to doors, the dock workers unload the shipments from origin trailers and load them on destination trailers. The dock supervisor also decides which trailers or shipments are assigned to which dock worker and the sequence the dock worker uses to load and unload the shipments. Each shipment may consist of multiple handling units, where each handling unit requires one trip from the origin trailer to the destination trailer.

Currently, for many LTL hubs, the assignment of trailers to dock doors is based on historical data and extensive experience, rather than actual shipping operations occurring that day. For example, the average number of shipments to a specific destination during a period may be analyzed to determine the shipment flows between origins and destinations. Then the origin and destination pairs with large shipment flows may be assigned close to each other. Alternatively, the destination trailers may be assigned to dock doors based on geography (such that Roanoke, Virginia, and Richmond, Virginia, doors may be adjacent). The assignment of destination trailers to dock doors is often relatively fixed during a period (such as 6 months), while the origin trailers are assigned to the doors as they arrive at the hub based on experience and the available doors. Ideally, to increase hub efficiency, the assignment of trailers to doors is based on the actual shipments for a given day, rather than historical shipment data.

After the trailers (origins and destinations) are assigned to dock doors, a dock worker is typically assigned to a trailer to remove a shipment and transport it on a forklift to the appropriate destination trailer. The dock worker then returns to the origin trailer with an empty forklift to unload the next shipment on the manifest. This unloading process, referred to as trailer-at-a-time, continues until an entire trailer is unloaded. The trailer-at-a-time approach is relatively straightforward to plan and execute, but often results in excess movements when the worker is traveling with an empty forklift. Alternative approaches for trailer-at-a-time may reduce the distance the worker travels with an empty forklift. For example, the worker might unload a shipment from an origin trailer, transport it on a forklift to the destination trailer, and then unload the shipment from another nearby origin trailer rather than return to the first origin trailer. Finding an optimal sequence of unloading and loading shipments in the hub operations is referred to as the freight sequencing problem (FSP).

The remainder of this paper focuses on the freight sequencing problem. Section 2 provides a more detailed description of the FSP. Section 3 reviews the relevant literature for both LTL hub operations and related problem in other contexts. Section 4 presents a mathematical formulation for the FSP, and Section 5 describes solution approaches for the FSP. Section 6 compares the FSP approaches using industry data sets. Finally, the conclusions of this research and future research directions are summarized in Section 7.

2 Problem Description

Given an assignment of trailers to dock doors and the number of dock workers at the hub, the objective of the FSP is to determine an optimal sequence for workers to unload shipments from origin trailers and load shipments on the corresponding destination trailers to minimize the time to transfer all shipments. Currently, the trailer-at-a-time approach is used extensively in practice and assumed by most research in the literature. The optimal sequence, however, might require a worker to unload a shipment from an origin trailer, transport it on a forklift to the destination trailer, and then unload the shipment from another trailer nearby. The following assumptions are used in addressing this problem:

- trailers are assigned to dock doors at the hub;
- the travel distance between dock doors is known;
- each handling unit requires one trip; and
- the speed of the forklift and unloading and loading time used for transferring shipments is constant.

The FSP can be modeled as a directed Rural Postman Problem (RPP). The RPP is a general case of the Chinese Postman Problem (CPP) in which a mail delivery person must cover all the arcs on his assigned segment before returning to the post office [4]. The objective of the problem is to determine the shortest walking distance for a mail delivery person [5]. Instead of considering all arcs for the delivery person, the RPP determines a tour for the delivery person to traverse only a subset of all arcs (called required arcs) at least once on the graph while minimizing the travel distance.

In the FSP, the origin and destination trailers are assigned to corresponding dock doors. Figure 1 illustrates a hub, where dark blocks represent the origin trailers and white blocks represent the destination trailers. The bold directed arcs represent forklift movements transferring shipment handling units from origin trailer doors to destination trailer doors, which are required trips. The dash directed arcs represent the empty forklift returns to the origin doors, which are non-required trips that may be accomplished in alternative ways. The required and non-required movements in the FSP correspond to the required arcs and non-required arcs in the RPP.

Using the RPP analogy, a network $G = (N, A)$ is defined, where N is the set of all nodes representing the doors that are assigned to origin and destination trailers and A is the set of all directed. Let R be the set of all required directed arcs, such that R is subset of A. The arcs in R are required arcs and the other arcs in $A \backslash R$ are non-required arcs (or empty travel arcs). The subgraph which includes the arcs of R, $G_R = (N, R \subseteq A)$. is a required subgraph. The cost c_{ij} ($c_{ij} \geq 0$) of traversing each arc (i, j) is the distance between node i and node j.

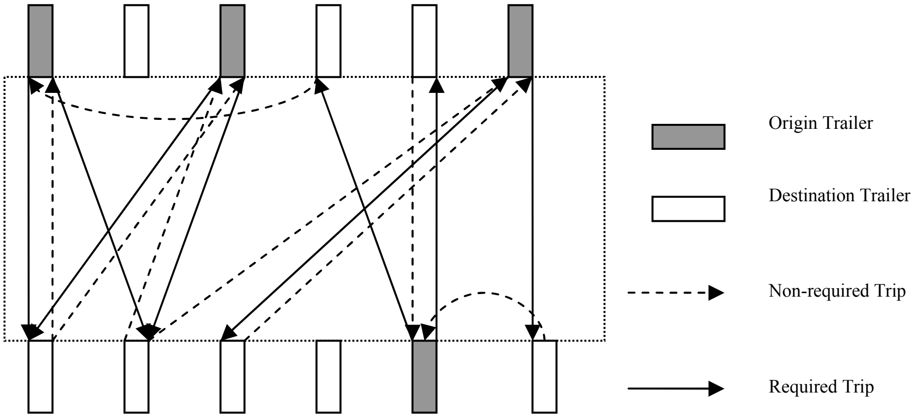


Figure 1: Required and Non-required Trips for Transferring Freight

From graph theory, an Euler cycle on a graph is possible if and only if every vertex on the graph is of even degree where the in-degree equals the out-degree [6]. Let node *i* be a door of the hub on the subgraph $G_R = (N, R \subseteq A)$. If node *i* is occupied by a destination trailer, the in-degree is the number of arcs entering the node and corresponds to the number of required shipments into node *i*. If node *i* is occupied by a origin trailer, the out-degree is the number of arcs exiting node *i* and corresponds to the number of shipments from node *i* to other nodes.

In the FSP, we assume that a worker starts at an origin trailer and ends at that origin trailer when all shipments are transferred. Thus, the problem is to find an Euler cycle for the worker where the number of arcs exiting a node is equal to the number of arcs entering the node. The objective is to minimize the total completion time (travel time and the unloading and loading time).

3 Literature Review

Most research on hub operations focuses on the trailer-to-door assignment problem. Peck [7] published some of the earliest work on the trailer-to-door assignment problem of hub operations, followed by research from Tsui and Chang [8][9], Gue [10][11], Bartholdi and Gue [12], Bermudez and Cole [13], Brown [14], Bozer and Carlo [15], and Tong [16]. Most of the research assumes a trailer-at-a-time approach for transferring shipments for the trailer-to-door assignment problem. Brown [14], however, introduces alternative approaches to address the FSP, and Tong [16] expands on these approaches. A portion of their research is presented in this paper.

The FSP is very similar to the component placement sequence problem in the printed circuit board (PCB) assembly industry. With the component placement sequence problem, components (chips) from the edge of the board are picked and placed by a numerically controlled placement head into different places on the board. The problem is to develop a sequence of picking and placing the components that minimizes the total operation time. While this problem was widely modeled as a traveling salesperson problem (TSP) in the literature, Ball and Magazine [17] modeled this problem as a RPP since placement head movements can be partitioned into required and non-required movements, which corresponds to the required and non-required arcs in the RPP network. Hence the goal is to find the Euler tour that minimizes the total distance. An efficient heuristic was developed and compared to the lower bound. Their approach was developed for a PCB placement machine that has one placement head and only one component can be placed at any given time. This is analogous to a single worker transferring the freight for hub operations.

Other applications of the RPP in the literature include contexts where streets or roads are traversed for maintenance, garbage collection, milk or mail delivery, school bus transportation, parking meter collection, electric meter reading, electrical lines and gas main inspection. Bodin and Kursh [18] describe a computer assisted system for routing and scheduling street sweepers, together with computational experiences derived from two pilot studies in New York City and Washington, D.C. Haslam and Wright [19] describe an algorithm used for the design of highway snow and ice control in Indiana. Stricker [20] developed a computerized arc routing algorithm for the urban waste collection problem which is also a RPP application. Polynomial algorithms exist for the CPP, but the RPP is NP-hard [21]. Thus, heuristic solution approaches are generally employed.

In summary, most research on LTL hub operations focuses on the trailer-to-door assignment problem rather than the FSP. Problems similar to the FSP, but in other contexts, have been explored by researchers. Approaches specifically for the FSP have been recently developed by Brown [14] and Tong [16], and some of these algorithms are described and compared in this paper.

4 Problem Formulation for a Single Worker

Using the RPP structure, a mathematical formulation is presented for the freight sequencing problem for a single worker. The following notation is used in the formulation:

i, j	indices for nodes (doors)
N	set of all nodes (doors)
R	set of required arcs
c_{ij}	travel distance between node i and node j
v	average forklift travel speed
f_{ij}	shipment flow (number of handling units) to transfer from node i to node j
d_i	the in-degree of each destination node and the out-degree of each origin node i
u_i	unloading time at node i
l_j	loading time at node j
x_{ij}	the number of arcs (i, j) used; an integer variable

The shipment data is analyzed to determine the number of trips or handling units, f_{ij}, required for transfer from node i to node j. For each node i with an origin trailer, d_i is the number of required arcs exiting the node such that $d_i = \sum_{j \in N} f_{ij}$. For example, if 5 handling units need to be transferred from node 1, then $d_1 = 5$. For each node i with a destination trailer, d_i is the number of required arcs entering the node such that $d_i = \sum_{j \in N} f_{ji}$. For example, if 7 handling units are transferred into node 3, then $d_3 = 7$. The problem is formulated as an integer programming model.

Minimize

$$\sum_{i \in N, j \in N} \frac{c_{ij}}{v} x_{ij} + \sum_{(i,j) \in R} \left(\frac{c_{ij}}{v} + u_i + l_j \right) f_{ij} \qquad (1)$$

Subject to:

$$\sum_{j \in N} x_{ij} = d_i \qquad \forall\, i \in N \qquad (2)$$

$$\sum_{j \in N} x_{ij} = d_i \qquad \forall\, i \in N \qquad (3)$$

$$\sum_{i \in N'} \sum_{j \in N - N'} x_{ij} \geq 1 \qquad N' \subset N, N' \neq \phi \qquad (4)$$

$$x_{ij} \geq 0 \qquad \text{Integer} \qquad (5)$$

The objective function (1) minimizes the total travel time for all non-required arcs on the network $G = (N, A,)$ and the travel time and the unloading and loading time for all required arcs. Travel time is estimated by the travel distance between node i and j (c_{ij}) divided by the average forklift travel speed v for the non-required arcs. For a required arc (i,j), the worker unloads the shipment at node i, resulting in unloading time u_i. The worker then travels to j with an associated travel time. The worker then loads the shipment at j, resulting in loading time l_j. These travel times, unload times, and load times are captured in the objective function. Constraint sets (2) and (3) ensure the graph is balanced. For each node, the number of entering arcs equals the number of exiting arcs. Constraint set (4) ensures the graph is connected. If constraint (4) is removed, a minimum cost network flow problem (MCNFP) emerges that can be solved using a standard MCNFP algorithm in polynomial time [17].

This formulation assumes that one worker is required to transfer all the shipments for all origin and destination trailers. Often, multiple dock workers are available to perform the freight transfer jobs during the night in a hub. Models and solution approaches for the freight sequencing problem (FSP) for multiple workers are described in Brown (2003) and Tong (2009). The following sections describe and compare solution approaches for the FSP for a single worker.

5 Solution Approaches for the Freight Sequencing Problem

In this section, two solution approaches for the FSP are presented and compared to trailer-at-a-time approach. These approaches are described for a single worker. These approaches assume that the origin and destination trailers are already assigned to dock doors at the hub.

5.1 Trailer-at-a-Time for the FSP

The trailer-at-a-time approach is a widely used process for unloading and loading shipment operations in the LTL hub. With this approach, a worker is assigned an origin trailer and transfers all the shipments on the origin trailer to the appropriate destination trailers before transferring shipments on another origin trailer. Each time a worker completes one shipment on a trailer, the worker returns to the same trailer for another shipment. After the worker transfer all the shipments on that trailer, the worker moves to another origin trailer to transfer the shipments on that trailer. This process continues until all trailers assigned to the worker are completed. The trailer-at-a-time approach for a single worker is summarized in the following steps:

Step 1: Worker is assigned to an origin trailer;
Step 2: The worker transfers the handling units for the first shipment on the trailer to the appropriate destination trailer;
Step 3: The worker returns to the same origin trailer to transfer the handling units for next available shipment;
Step 4: Go to Step 3 until no shipments remain on the origin trailer; and
Step 5: Go to Step 1 until no origin trailers need to be unloaded.

The trailer-at-a-time approach provides a practical solution for the FSP that is easily implemented in hub operations. The hub manager simply assigns trailers to workers and workers complete individual origin trailer without any predetermined freight unloading and loading sequences. The disadvantage of this approach is that the travel distance of empty forklift movements might be unnecessarily long, compared to the travel distance with more efficient freight sequencing approaches, resulting in more time to transfer all shipments.

5.2 Nearest Neighbor Algorithm for the FSP

As an alternative, construction heuristics can be used to develop a solution for the FSP in a progressive manner. With a construction heuristic, a partial solution is obtained and an extension of this solution is constructed by selecting one of a number of options available. A well-known construction heuristic is the nearest neighbor algorithm, which is frequently applied to the related traveling salesperson problem (TSP). For the TSP, suppose that a partial tour has been constructed in previous iterations. This open tour has two ends such that two cities that are currently linked only with a single city. One of these two cities is then linked to the city that is closest. This algorithm is myopic since it only considers the best possible next step. This construction heuristic quickly generates a tour, but not necessarily an optimal tour.

The nearest neighbor algorithm can be adapted for the freight sequencing problem [14]. When the nearest neighbor algorithm (NNA) is applied to the FSP, a required arc is always selected (rather than going to any nearest neighbor). At each destination trailer node, the worker selects the closest origin trailer node that has shipments remaining. The nearest neighbor algorithm for the FSP is summarized in the following steps:

Step 1: Set up a network $G = (N, R)$ where N is the set of doors which contain the origin and destination trailers and R is the set of all required trips. Select an origin trailer.
Step 2: Transfer a shipment on the manifest to the appropriate destination trailer.
Step 3: Select the origin trailer with shipments remaining which has the shortest distance from the current trailer, go to that origin trailer and transfer a shipment.
Step 4: Repeat Step 3 until no shipments remain on the manifest.

The nearest neighbor algorithm is easy to implement and executes quickly. Due to its myopic approach, however, the nearest neighbor algorithm sometimes misses shorter routes which are easily noticed with human insight [22].

5.3 Balance and Connect Algorithm for the FSP

The balance and connect algorithm is adapted from an approach presented by Ball and Magazine (1988) for a similar problem in electronic assembly systems. In the mathematical formulation of the FSP, constraint set (4) assures that the network is connected. If this constraint is removed, a minimum cost network flow problem (MCNFP) remains that can be solved using a network flow algorithm. After the minimum cost network flow problem is solved to generate a balanced network, several disconnected subtours may exist. If subtours are found, a minimum spanning tree algorithm can be used to generate a connected graph which contains an Euler tour. Using an Euler tour finding procedure, a tour is generated to determine the worker's sequence of unloading and loading shipments. The balanced network is found first and then the network is connected if subtours exist, and the procedure is referred to as the balance and connect algorithm. This sequential approach produces an approximate solution to the FSP that may not necessarily be optimal since it does not address the interaction between the balancing and connecting steps. The balance and connect algorithm (BCA) is summarized as follows:

Step 1: Setup the directed RPP network $G_R = (N, R)$.
The directed RPP network $G_R = (N, R)$ is established, where $N = \{1, 2, \ldots i, \ldots n\}$ is the set of doors with assigned origin and destination trailer and R is the set of all required arcs.

Step 2: Determine the in-degree or out-degree for each node on the network.
For each node i with an origin trailer, d_i is the number of required arcs exiting the node such that $d_i = \sum_{j \in N} f_{ij}$. For each node i with a destination trailer, d_i is the number of required arcs entering the node such that $d_i = \sum_{j \in N} f_{ji}$.

Step 3: Solve the relaxed FSP problem (formulation (1) – (5) without constraint (4)).
The solution from the MCNFP provides the required arcs and non-required arcs so that $G = (N, A)$ is balanced.

Step 4: Check the connectivity of the resulting graph $G = (N, A)$.
Using a procedure from Scheinerman [6], check the connectivity of graph $G = (N,A)$. Assume all nodes are in list K (nodes to be explored). Select some node x to place in list L. Build a list (L) of the nodes which can be reached from x. Each time a new node is added to this list (L), the neighboring nodes are checked to see if they should be added. Finally the list is checked to see if the list covers the whole graph. If nodes remain in K, start from another node which is not in L and repeat the above again until all subtours are found.

Step 5: Connect the subtours in the graph $G = (N, A)$.
If disconnected subtours are found, a minimum spanning tree algorithm [23] is used to identify the set of edges (M) to connect the subtours. For each spanning edge that connects the subtours, make two copies of this edge, associating one direction with one edge and the opposite direction with the other edge.

For example, assume two subtours are identified as follows: (1, 2, 3, 4) and (5, 6, 7) as shown in Figure 2. Using the minimum spanning tree algorithm, edge (3, 5) is found to connect two subtours. Two copies of edge (3, 5) are created with opposite directions to connect the network and ensure the network is balanced.

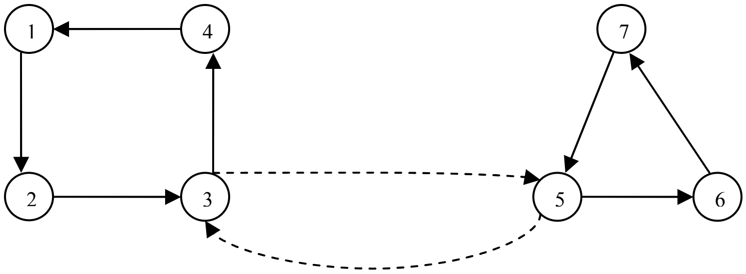


Figure 2: Connect the Subtour

Step 6: Form a graph that consists of all required arcs and selected non-required arcs such that $G = (N, A \cup M)$.

Required arcs, non required arcs, and the arcs to connect subtours form a network $G = (N, A \cup M)$. This network serves as the basis for the next step to find a sequence.

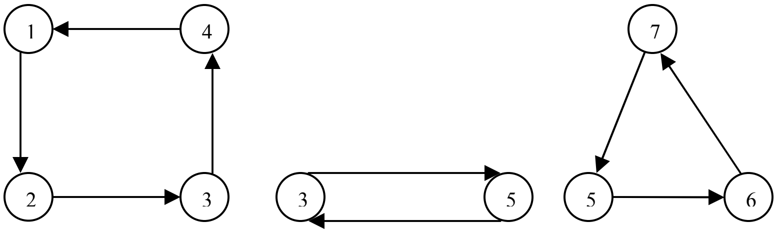
Step 7: Apply Euler tour algorithm to find a sequence.

Several Euler tour algorithms [24] [4] [6] can be used to construct an Euler tour to find a sequence for the worker. In this research, an algorithm from Scheinerman [6] is used. This algorithm is based on the observation that if C is any cycle in an Euler graph, then after removing the edges of C, the remaining connected components will also be Euler graphs. The algorithm can be summarized as follows:

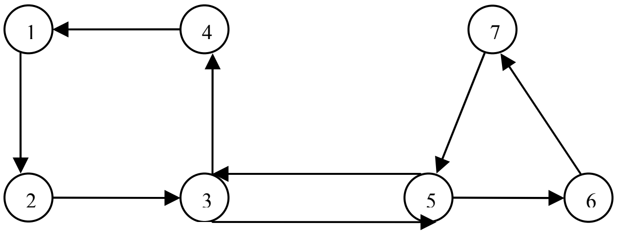
a. Find all cycles on the graph G; and
b. Splice the cycles to form an Euler tour.

Assume three cycles are found as follows: (1→2→3→4→1) (3→5→3) and (5→6→7→5). Using the Euler tour construction algorithm, the three cycles are spliced at node 3 and 5: (1→2→(3→(5→6→7→5)→3)→4→1). As illustrated in Figure 3, the resulting Euler tour is 1→2→3→5→6→7→5→3→4→1.

To implement the balance and connect algorithm for hub operations, a list of shipments (indicating the shipment number, the number of handling units for this shipment, the origin trailer and destination trailer for this shipment) is needed. After the unloading and loading sequence is found from the algorithm, the sequence associated with each shipment is added to the shipment list. This shipment sequence list is used for the worker to unload and load shipments accordingly. Although the balance and connect algorithm generates a feasible tour to transfer the shipments, the tour may not necessarily be optimal.



a. Find all cycles on the graph



b. Splice the cycles to form an Euler tour

Figure 3: Developing the Euler Tour

6 Results for the FSP for a Single Worker

Using five industry data sets, the trailer-at-a-time approach, the nearest neighbor algorithm, and the balance and connect algorithm are compared. The characteristics of the data sets are summarized in Table 1. For each data set, the trailer-to-door assignment problem is solved using the dynamic approach with simulated annealing [14] [16].

Table 1: Data Sets for Case Study for the FSP

Data Set	Origin Trailers	Destination Trailers	Number of Shipments	Dock Doors
1	16	15	178	31
2	16	15	178	31
3	16	16	201	32
4	17	17	173	34
5	62	33	652	95

The trailer-at-a-time approach and the nearest neighbor algorithm are implemented in C++ and executed on an Intel Pentium 4 2.8 GHz computer. For the balance and connect algorithm, the formulation (1) – (5) without constraint (4), is formulated in AMPL and solved using CPLEX 10.0 on an Intel Pentium 4 2.8 GHz computer. The solution is then checked for connectivity, and the minimum spanning tree algorithm [23] is applied to connect the subtours if necessary.

The total travel distance (feet) for the trailer-at-a-time (TAAT), nearest neighbor algorithm (NNA) and the balance and connect algorithm (BCA) are summarized in Table 2. For these data sets, both the NNA and the BCA outperform TAAT. Also, the BCA outperforms the NNA. The percentage improvement of the BCA over the TAAT in terms of total travel distance varies from 10% to 27%. These results demonstrate the substantial opportunity for reducing the total distance traveled by workers during hub operations using alternative freight sequencing approaches.

Table 2: Total Travel Distance for Heuristics for Single Worker FSP

Data Set	TAAT (feet)	NNA (feet)	BCA (feet)	NNA Reduction over TAAT	BCA Reduction over TAAT
1	100284	98015	89137	2.3%	11.1%
2	99954	99821	89726	0.1%	10.2%
3	79072	77821	68908	1.6%	12.9%
4	44892	44791	37117	0.2%	17.3%
5	477699	472312	349132	1.1%	26.9%

The results of total transfer time (in minutes) for the trailer-at-a-time (TAAT), nearest neighbor algorithm (NNA), and the balance and connect algorithm (BCA) are summarized in Table 3. As shown, both the NNA and BCA outperform the TAAT for total transfer time as well. Also, the BCA outperforms the NNA. The percentage improvement of the BCA over the TAAT ranges from 3% to 10%. The improvements on the total transfer time for the BCA are not as substantial as the improvements on the total travel distance from the BCA. The total transfer time includes the travel time, along with the unloading and loading times. Since the unloading and loading times are fixed times, the improvements for the total transfer time are limited by these fixed times. Thus, the improvements by the NNA and BCA are not as substantial for this measure as for the total travel distance.

Table 3: Total Transfer Time for Heuristics for Single Worker FSP

Data Set	TAAT (min)	NN (min)	BCA (min)	NNA Reduction over TAAT	BCA Reduction over TAAT
1	2079	2040	1991	1.8%	4.2%
2	2064	2053	2001	0.5%	3.1%
3	1568	1558	1516	0.6%	3.3%
4	803	800	768	0.4%	4.4%
5	5766	5743	5201	0.4%	9.8%

7 Conclusions and Future Research

Unloading and loading shipments is an integral part of hub operations in the less-than-truckload freight transportation industry. In this paper, the freight sequencing problem is modeled as a Rural Postman Problem (RPP) and two algorithms are presented. The nearest neighbor algorithm (NNA) and the balance and connect algorithm (BCA) are developed and compared to the trailer-at-a-time (TAAT) approach often used in industry. Using five industry data sets, the NNA and BCA algorithm are shown to improve both total travel distance and total transfer time compared to the TAAT. The BCA also outperforms the NNA for these data sets. The results demonstrate the potential improvement for hub operations using alternative freight sequencing methods.

The results also highlight opportunities for future research. In some cases, the unloading process is constrained by precedence due to the order that the shipments are physically placed in the trailer. For example, if shipment 2 is physically placed in the trailer behind shipment 1, then in the shipment sequence, shipment 1 should be transferred before shipment 2 is transferred since it is not practical for the worker to take shipment 2 out of trailer before transferring shipment 1. For the TAAT and NNA, the precedence constraints are easily ensured. With the BCA, however, the precedence constraints may not be ensured without adjustment. This provides opportunities for future research to the FSP. Also, most hubs have multiple workers transferring shipments. Research on the FSP for multiple workers has been initiated by Brown [14] and Tong [16], but additional research opportunities remain.

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