A Comparison of Three Popular Routing Policies for Lift-truck Order Picking

Vitaly Brazhkin, and William J. Rose

Abstract

This study addresses order-picking routing optimization in a wide aisle of a mechanized warehouse. Efficiencies of the three popular heuristic policies (return, traversal, and Z-pick) are compared for different pick densities. A modified Z-pick policy with a flexible string length is proposed to increase its efficiency and accommodate lift-truck movement. The simulation-based results show that all three policies are not significantly different in the pick density region of 10–15 percent. The traversal policy performs better at pick densities below the region of indifference, while the return policy outperforms the others at higher pick densities. However, the Z-pick provides a viable universal alternative across all tested pick densities.

Keywords
warehouse operations, order picking, routing policy, lift truck, simulation

Warehouses experience constant pressure to deliver more with less, specifically, to process and ship orders faster at a lower cost (Newsome, Thompson, and Commander 2013). Despite productivity growth, with 1,000 picks per manhour possible in some operations, managers still seek efficiency improvements (De Koster, Le-Duc, and Roodbergen 2007). Order picking presents a significant opportunity for cost reduction (Guia and Tan 2019), as travel between storage locations, while necessary, adds no value but accounts for half of the total picking time (Tompkins et al. 2003).

Given a picklist with items and storage locations, routing policies determine picking tour travel times by sequencing the locations a picker

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visits. Order-picking problems represent a special case of the traveling salesman problem (TSP) solvable with optimization methods or heuristics (Petersen and Schmenner 1999; Çelik and Süral 2016). Several factors influence routing policy choice, including transportation mode, aisle width, and the number of items picked in an order. This article focuses on distribution centers that utilize manually operated order-picking trucks in wide aisles, typical of the automotive and furniture industries (Brazhkin 2018). Furthermore, the article uses simulation modeling to compare three popular order-picking heuristics across multiple order sizes to answer the research question: how does pick density influence order-picking policy performance?

The study contributes to both theory and practice in several areas. First, the article presents an alternative form of the Z-pick heuristic originally presented in 1988 (Goetschalckx and Ratliff 1988), which provides a compromise between the traditional traversal and return policies. Further, the study offers insight for warehouse managers in selecting routing policies that reduce picking time, improving both costs and customer-service levels by removing unnecessary travel. Finally, managers cannot choose a routing policy in isolation. The choice of the routing policy impacts and is impacted by a number of factors, including storage organization and warehouse layout (Žunić et al. 2018).

The article is structured in the following way. A literature review is presented in the next section, followed by a problem formulation and a description of the updated Z-pick heuristic. Next, the methods section describes the simulation model and is followed by findings. The article concludes with a summary of results and recommendations and a review of the study limitations.

Literature Review and Paper Positioning

With its high impact on order-picking efficiency (De Koster, Le-Duc, and Roodbergen 2007), routing policy selection enjoys a greater presence in recent research than other key warehousing decisions such as warehouse layout, slotting, and order batching (Masae, Glock, and Grosse 2020). The order-picking problem is often classified as a special case of the TSP with an objective of minimizing the distance required to visit selected storage locations (Çelik and Süral 2016). The TSP has been studied for a variety of settings, for example, urban waste collection, and is generally recognized as NP-hard (Tirkolaee, Mahdavi, and Esfahani 2018).

However, certain simplified cases of the problem for a number of warehouse settings were shown to have polynomial solutions (Celik and Süral 2016). Ratliff and Rosenthal (1983) proposed an optimal algorithm for a simple, single-block warehouse and others extended this initial work to incorporate repeated visits to a single storage location (Cornuéjols, Fonlupt, and Naddef 1985), multiple order deposit points (De Koster and Van der Poort 1998), and additional cross-aisles (Roodbergen and De Koster 2001). These optimal solutions assume narrow aisles that allow a centrally positioned picker to access items on either side (Ratliff and Rosenthal 1983; Masae, Glock, and Grosse 2020). Alternatively, a wide-aisle order-picking problem requires side-to-side movement at least once during the picking tour (Goetschalckx and Ratliff 1988), adding a layer of complexity to existing order-picking problems.

For the majority of warehouse settings, the TSP for order picking is considered an NP-hard problem, precluding the use of exact algorithms (Theys et al. 2010). In response to this issue, many warehouse managers turn to simple heuristics (De Koster, Le-Duc, and Roodbergen 2007). Heuristics are easier to understand and implement (De Koster, Le-Duc, and Roodbergen 2007; Masae, Glock, and Grosse 2020) and provide adequate, and often near-optimal solutions. Common heuristics for the wide aisle problem include the traversal, return, and Z-pick policies (Goetschalckx and Ratliff 1988).

Under the traversal policy the order picker enters the aisle and progressively visits storage locations, always selecting the location nearest the entry point and crossing the aisle as necessary (Hall 1993). The picker then exits at the opposite end, enters the closest end of the next aisle, and continues picking. Figure 1 illustrates the traversal policy. Extended over multiple aisles, the traversal policy creates a route resembling the letter S when viewed from above and resulting in an alternate name of the "S-shaped" policy (De Koster, Le-Duc, and Roodbergen 2007). Pickers following the return policy enter the aisle and visit picking locations on one side first, then turn around and re-enter the same aisle, picking from the other side as they return to the entry point. The return policy is shown in figure 2.

The Z-pick heuristic combines key elements of both the traversal and return policies. Similar to traversal, the picker crosses the aisle at least once before exiting. On the other hand, the picker remains on one side of the aisle longer than with traversal, potentially passing items on the opposite side, as under the return policy. Movement continues on one side until the picker visits a preset number of locations, called a string length (Goetschalckx and

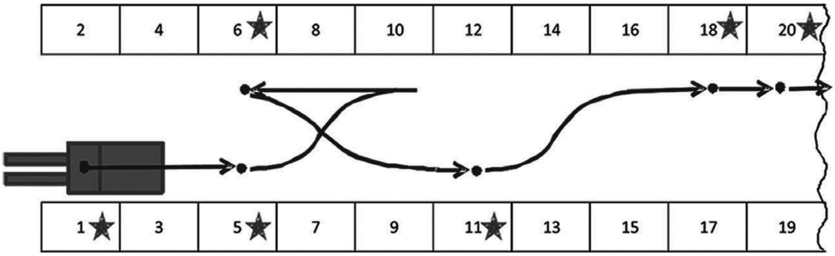

Figure 1 Example of the traversal routing policy (locations to visit are marked with stars)

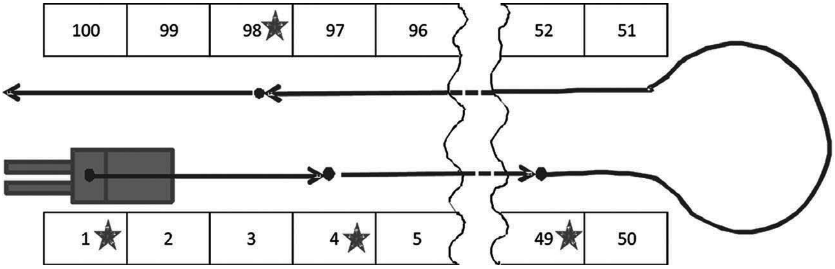

Figure 2 Example of the return routing policy (locations to visit are marked with stars)

Ratliff 1988). Reaching the string length triggers an aisle crossing at which point the picker moves in reverse to visit storage locations already passed. This combination of forward movement along the side of an aisle and reverse movement to cross resembles the letter Z (fig. 3), hence the name Z-pick. At lower pick densities, the Z pattern may become distorted, but the reverse movement to reach missed locations differentiates the Z-pick policy from both return and traversal.

The traversal and return policies seek to reduce unnecessary movement within the pick tour. Thus, comparing the two requires an examination of factors that extend travel distance. Aisle width influences travel distance, but the tradeoff between multiple aisle crossings with the traversal policy and skipped locations from the return policy further impacts picking performance. Travel distance under a return policy remains consistent regardless of the number and location of picks as the picker travels the entire distance of the aisle, crosses the aisle, and then returns across the same distance. With the traversal policy, though, increased pick density, or the percent of storage locations to visit, requires more frequent crossovers.

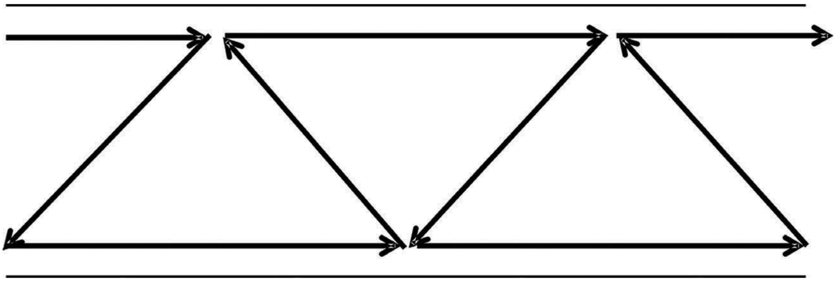

Figure 3 Fixed Z-pick routing policy

As a result, at lower pick densities the traversal policy's single trip down an aisle requires less travel than the two trips associated with a return policy, leading managers to select the traversal policy. As pick densities and aisle crossings increase, the added movement across the aisle eventually outweighs the return policy's bi-directional travel, creating a preference for the return policy (Goetschalckx and Ratliff 1988).

Previous research examines the relationship between pick density and routing policy, showing that the shift from traversal to return should occur at a pick density of about 65 percent, but that the Z-pick policy never outperforms both traversal and return (Goetschalckx and Ratliff 1988). One reason for the Z-pick policy's poor performance may be the original heuristic's design. Following a "fixed" Z-pick policy, pickers ignore the locations of pick items and instead follow a strict pattern (Goetschalckx and Ratliff 1988). The current work incorporates a different trigger for crossing an aisle based on the distance between the lift truck's location following a pick and the item nearest the entry point on the aisle's opposite side.

Aisle and storage location widths directly impact the distance traveled in a pick tour, but the mode of transportation further influences routing policy decisions. Most order-picking solutions model walking pickers (Masae, Glock, and Grosse 2020). According to one review, less than 5 percent of academic papers on warehousing consider lift trucks (Burinskiene 2015). With that said, several lift-truck parameters influence not only the distance traveled in a pick tour but also the time required to complete it.

Walking allows a picker to move at a constant speed and turn at a right angle at any given time. Lift trucks require time to accelerate to a cruising speed and decelerate when stopping, removing the direct relationship between distance and time assumed in many routing solutions (Fleming, Griffis, and Bell 2013) and adding further complexity to the order-picking problem (Kunder and Gudehus 1975). Additionally, lift trucks slow down to turn, with speeds decreasing as much as 80 percent (Çelik and Süral 2016), and often require some forward movement to execute a turn (Chabot et al. 2017). As a result, the 90-degree turns assumed in prior research on the traversal policy no longer hold when modeling lift-truck movement in a wide aisle. Finally, modeling lift-truck operations requires an adjustment to accommodate the size of the lift truck and a recommended safety gap between the lift truck and racks, reducing aisle width and impacting both travel distance and time (Burinskiene 2011, 2015).

Prior research introduces several factors that influence the order-picking problem but lacks a single study to incorporate all factors in a single, true-to-life model of order picking with lift trucks (Masae, Glock, and Grosse 2020). The current work models lift-truck movement while considering the vehicle's turning radius, acceleration, deceleration, maximum forward and reverse speeds, and size. Additionally, the paper answers a separate call for research on the Z-pick policy with flexible string lengths (Goetschalckx and Ratliff 1988). Figure 4 presents the paper's intended contribution to the order-picking problem literature.

Problem Formulation

The Z-pick policy represents a compromise between the traversal and return heuristics. Similar to the other traditional order-picking heuristics, a picker arrives at a storage location and then chooses the next location to visit. Under the return policy, the picker always chooses the next location on the same side of the aisle while the traversal policy dictates the picker choose the nearest location to the entry point regardless of side. The Z-pick allows the picker to pass some storage locations without having to travel the entire length of the aisle twice. The heuristics defining factor is a string length beyond which the picker chooses to cross the aisle. The original Z-pick solution determined string length based on the number of consecutive storage locations visited on one side of an aisle (Goetschalckx

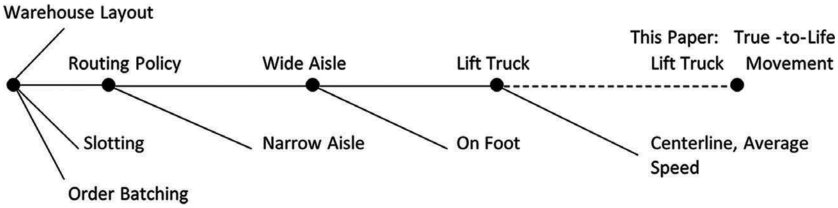

Figure 4 Paper contribution to the picking optimization literature stream

and Ratliff 1988), which hindered the heuristic's performance overall. We propose an alternate string length that incorporates lift-truck parameters and the distance required to cross an aisle.

After arriving at a storage location, the picker measures the distance between their current location and the storage location on the opposite side of the aisle nearest the entry point. If the lift truck's turning radius allows the picker to cross the aisle in reverse without passing the storage location nearest the entry point, the picker crosses the aisle. Otherwise, the picker moves to the next storage location on the same side of the aisle. Pseudo code for the adapted Z-pick heuristic policy is provided in appendix A and figure 5 provides an example problem to illustrate the heuristic.

The picker first travels to location 5, then decides whether to cross the aisle to reach location 6 or move forward directly to location 7. Under the traversal policy, the picker crosses the aisle to location 6, then immediately crosses back to reach location 7. In this example, with a string length of three slot widths, the picker moves forward to location 7 instead. At location 7, only one slot width separates the picker's current location from location 6 and the picker chooses to move forward to location 11. On arriving at location 11, though, the picker crosses the aisle in reverse to reach location 6, three slot widths behind the current storage location. At the end of the aisle, or location 20, the picker again travels in reverse across the aisle to visit the final storage location (15) even though this represents a smaller movement than the string length would normally allow.

Several factors influence the correct string length for a Z-pick and its performance against other order-picking policies. To examine some of these factors and seek the inflection point at which routing policy preferences change, a simulation model compares multiple pick densities and policies in a single, wide aisle.

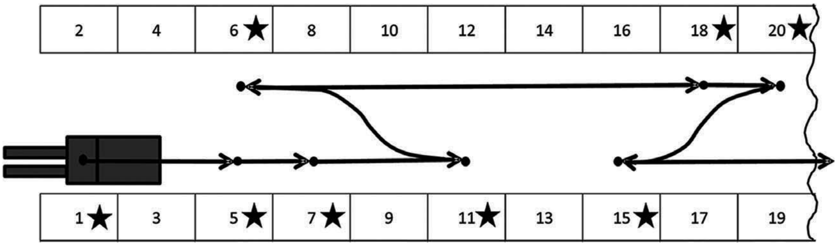

Figure 5 Example of the flexible Z-pick policy (locations to visit are marked with stars)

Method

The current research uses a simulation model to compare routing policies across multiple pick densities. Simulation presents an attractive method by providing the ability to tolerate realistic and complicated modeling assumptions and create a model reflecting complexity that cannot be approached by mathematical-analytical means (Kelton 2016). Further, simulation allows the researcher to design and control a system, allowing the research to focus on the most important factors to consider (Evers and Wan 2012).

Simulation Model

For this study, the simulation, built using AnyLogic University Researcher Edition 8.7.6, models a single aisle in a warehouse. The aisle includes two racks, set five meters apart, each containing a single-layer of fifty 1-m pick locations (Merkuryev, Merkuryeva, and Burinskiene 2009). The simulation uses lift-truck specifications from the Jungheinrich ECE 310 low-level order picker with ergonomic lift (Jungheinrich 2022). Table 1 displays lift-truck and aisle parameters as well as the pick density, or number of slots included in the lift truck's route.

Lift trucks travel forward and backward in straight lines, leaving a 0.1-meter safety gap between the lift truck and the rack itself (Çelik and Süral 2016). With this safety gap on either side, along with the 0.8-meter width of the lift truck itself (Jungheinrich 2022), crossing the 5-meter aisle requires four meters of horizontal movement. This aligns with prior research on lift-truck

Table 1/Warehouse and Lift Truck Data

Parameter	**Value**
Warehouse	
Effective aisle width	4 m
Aisle length	50 m
Total picking locations	100
Distance between centers of two adjacent picking locations	1 m
Distance from entry or exit point to center of nearest location	1 m
Lift Truck	
Maximum linear forward speed	2.8 m/sec
Maximum speed for maneuvering and backing	1.4 m/sec
Turnaround time, outside the aisle only	10 sec
Acceleration (Deceleration)	0.4 (-0.4) m/sec^2

routing that assumes at ratio of 4:1 between the aisle width and picking slot width (Goetschalckx and Ratliff 1988). Given the lift truck's turning radius, moving four meters across the aisle also requires four meters of forward or reverse movement. The key aisle parameters are presented in table 1.

The simulation starts by randomly selecting a set number of pick slots determined by the pick density parameter. After slot selection, the model dispatches a lift truck from a starting location one meter from the end of the rack containing the nearest pick slot. The lift truck then travels to the first assigned slot before coming to a complete stop. As pick times for items remain consistent across all scenarios, the model records only travel time between pick locations. On reaching the first assigned slot, one of three routing policies determine further lift-truck movement. The process logic for each policy is described further and illustrated in the form of a decision tree in appendix B.

Under the return policy, the lift truck remains on the same side of the aisle until it reaches the end of the rack, stopping at each assigned pick location. At the rack's end, the lift truck turns around and re-enters the aisle on the opposite side, facing the opposite direction. The model assumes two seconds for the driver to check for cross traffic and eight seconds for the lift truck to turn around, adding ten total seconds to the return policy scenario.

With the two remaining routing policies, the lift-truck driver either moves forward or crosses the aisle. Following the traversal policy, the lift truck always travels to the assigned slot with the lowest number. If the slot falls on the opposite side of the aisle, the lift truck first crosses the aisle, arriving four meters, or four slot-widths, closer to the end of the aisle than the lift truck's last stop. If the assigned pick slot falls four meters ahead of the lift truck's last stop, the lift truck stops at this slot to pick the item. Otherwise, the lift truck either continues forward motion or stops and moves in reverse until reaching the next assigned pick slot. The process repeats until all items are picked and the lift truck moves forward to the end of the aisle.

Similarly, the Z-pick policy uses the lift truck's current location to determine the next stop. A crossing parameter, four meters in the original model, sets a threshold for aisle crossing. If the assigned slot nearest the entry point falls more than four meters from the lift truck's current location, the lift truck crosses the aisle, moving in reverse. The turning radius for forward and reverse movement remains the same, thus the lift truck arrives at the opposite rack four meters behind its last stop. After reaching the opposite rack, the lift truck either continues moving in reverse to reach the next slot or comes to a complete stop to pick an item. With the parameter ensuring the vehicle moves at least four meters beyond a slot before crossing, the Z-pick policy never allows the lift truck to pass the assigned slot while moving in reverse. Thus, no forward movement occurs between crossing the aisle and reaching the next assigned slot. This repeats until all items are picked, at which point the lift truck travels to the end of the aisle and the total travel time is recorded.

The model measures the number of seconds required for the lift truck to travel to, and stop at, each assigned pick slot before moving to the ending location. Prior research assumes constant travel speeds, equating travel distance and time (Goetschalckx and Ratliff 1988). On the other hand, this simulation allows the lift truck to accelerate and decelerate, only moving at a constant, maximum speed when travel distances allow. When the lift truck lacks the space to reach maximum speed and slow to a complete stop at the assigned slot, the lift truck accelerates until it reaches the exact mid-point between picks, then decelerates to a stop. The model sets maximum forward linear speed at 2.8 m/s (Burinskiene 2015; Jungheinrich 2022) and half that speed (1.4 m/s) when maneuvering or moving in reverse (Çelik and Süral 2016). Table 1 provides lift-truck movement parameters and appendix C offers more detailed travel time and speed calculations.

Table 2 shows the parameters governing the simulation model. The model tested the three routing policies at pick densities of 7–50 percent, increasing at 1 percent increments. For each simulated scenario, 50 initial runs were conducted and analyzed to determine data precision. Initial analysis supports the use of 50 replications per simulated scenario to properly estimate outcomes at a specified precision (Law, Kelton, and Kelton 2007; Closs, Nyaga, and Voss 2010).

Furthermore, the simulation was subjected to verification and validation checks (Closs, Nyaga, and Voss 2010; Sargent 2013; Castillo et al. 2018). First, conceptual model validity was supported through interviews with lift-truck experts and on-site observations at a warehouse. Additionally, computerized model verification involved checking individual travel times against travel time calculations and comparing those to simulated results. Excel models measuring travel time across randomly assigned picked slots further provide support for computerized model verification. This process confirmed the model operated according to the logic presented. Operational validity was checked using parameter variation sensitivity analysis (Sargent 2013). For example, when slot widths were increased or maximum speed decreased, overall travel time increased across all scenarios. Similarly, travel time decreased across all scenarios when changes were

Table 2/Mean Travel Times for the Three Routing Policies (in seconds)

Density	**Return**	**Traversal**	**Z-Pick**	**Density**	**Return**	**Traversal**	**Z-Pick**
7	96.17558	**79.44843**	85.46973	29	**174.4302**	231.4338	195.6149
8	100.678	**83.68101**	90.63273	30	**176.5146**	240.781	198.9429
9	105.379	**89.87199**	100.0286	31	**179.5575**	249.6726	203.0406
10	109.0093	**95.37161**	108.9511	32	**182.4809**	262.2782	207.8439
11	113.7513	**102.6742**	112.4807	33	**185.3059**	269.6569	209.8209
12	117.7751	109.0896	115.2343	34	**187.8568**	277.0811	213.4832
13	121.3586	115.3827	123.3361	35	**191.0401**	290.3924	217.5093
14	125.2533	120.8076	129.6445	36	**192.9497**	292.2557	222.1609
15	129.1841	127.8585	136.3869	37	**195.4103**	308.7892	225.1615
16	**132.4891**	137.6899	141.3073	38	**198.2613**	309.1161	228.4455
17	**136.1492**	141.3435	147.2033	39	**200.8626**	321.0311	231.5523
18	**139.469**	147.8267	148.9997	40	**203.1925**	330.47	234.5088
19	**143.4215**	155.4497	154.4564	41	**206.1892**	337.4199	238.892
20	**145.9256**	162.5909	157.721	42	**208.4138**	351.9241	239.5153
21	**150.2892**	169.947	163.5603	43	**211.279**	360.9763	243.9698
22	**153.2654**	176.6992	168.6687	44	**213.3374**	367.0416	248.4278
23	**155.8937**	186.6734	173.6197	45	**215.8688**	386.3528	252.5085
24	**159.2**	195.8009	176.1905	46	**218.3227**	387.7113	254.2736
25	**162.0722**	195.6346	179.7793	47	**220.8906**	403.83	257.1528
26	**165.3326**	210.5769	182.2627	48	**223.4402**	411.1036	259.1972
27	**167.9915**	213.9326	187.0891	49	**225.2329**	423.3698	265.1354
28	**171.2285**	222.8698	192.7971	50	**227.9488**	435.3038	265.5216

Note: Values in bold indicate significantly lower travel times than all other policies tested.

made in the opposite direction. Finally, data validity was ensured through the use of existing industry parameters for lift trucks (Jungheinrich 2022) and data determined through observations as well as further parameter sensitivity analysis (Sargent 2013; Castillo et al. 2020).

Findings

Simulation Results

Following the simulation, an ANOVA analysis, including a comparison of confidence intervals of mean difference, was performed to determine the points at which policies differ significantly. The simulation results are presented in table 2 and figure 6.

At low densities, the traversal policy outperforms both the return and Z-pick policies. A region of indifference, with no routing policy showing

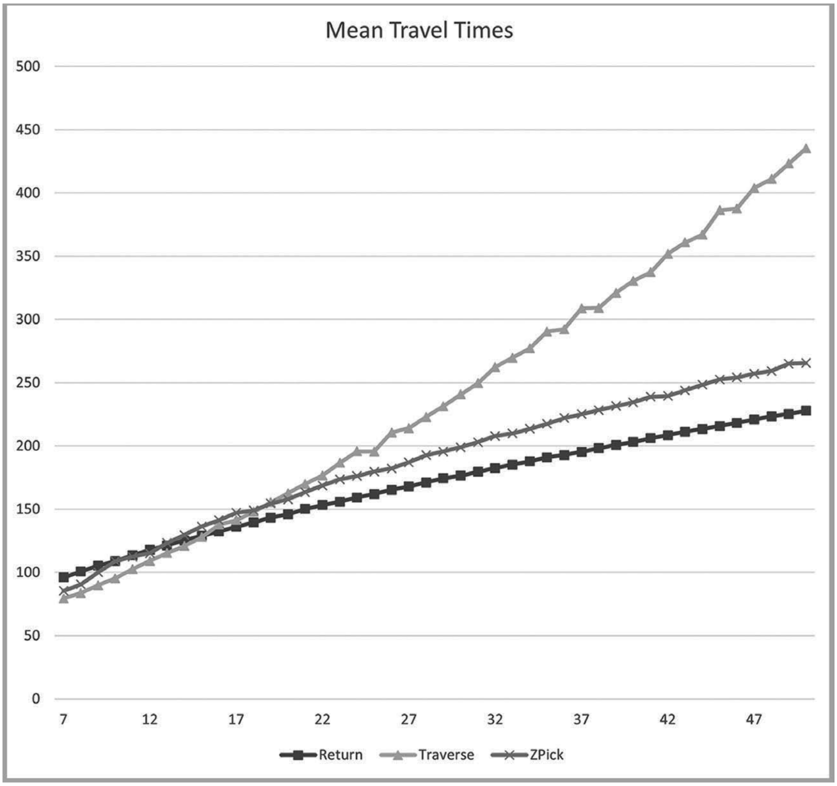

Figure 6 Mean travel times for the return, traversal and Z-pick routing policies (vertical axis, in seconds) for different pick densities (horizontal axis, in percent).

a significant advantage over the others, occurs from 10 to 15 percent. As pick density increases further, travel times under the return policy are significantly lower than those of the alternative heuristics. These results highlight the impact of aisle crossings reducing and eventually negating the traversal policy's initial advantage. As with the simulation of walking pickers (Goetschalckx and Ratliff 1988), the Z-pick policy never provides the best results but remains near the best option throughout all pick densities.

Theoretical Implications

The research re-examines the concept of string length in the Z-pick policy. The proposed string length incorporates aisle crossing distance and lift-truck parameters, maintaining the string length parameter after a single calculation. The updated heuristic provides an option for a single trip down an aisle with fewer crossings and skips each storage location at most one time. Simulation results show that the updated Z-pick heuristic creates pick tours that accommodate unidirectional movement through a warehouse aisle at a significantly lower cost than the traversal policy at high densities and significantly lower costs than the return policy at lower densities.

The second implication, which appears to have been completely overlooked by academic research, is the numbering of locations within the aisle. To generate pick lists, most warehouse management systems simply sort the addresses of the picking locations to visit in the ascending order. Locations are traditionally numbered in such a way that odd-numbered locations are on one side of the aisle and even-numbered locations are on the other side of the aisle, as shown in figure 1. This works perfectly for the traversal policy, which Goetschalckx and Ratliff (1988) showed to be superior for manual picking. However, our study for lift-truck picking showed that the return policy makes better sense starting from pick densities of 16 percent, but it will not work with numbering locations in this way. Rather, their numbers should increase to the end of the aisle on one side than continue from that point back to the beginning of the aisle on the other side, as shown in figure 2. This means that sections of a warehouse designated for products with high pick density that will likely use the return routing policy should be numbered accordingly.

Managerial Implications

For managers employing lift trucks in wide-aisle warehousing operations, the research presents several important contributions. First, while prior research recommends maintaining a traversal policy for on-foot picking up to and including high pick densities (Goetschalckx and Ratliff 1988), maneuverability constraints and speed variations associated with lift trucks shift the region of indifference to a much lower pick density when considering a shift from the traversal to the return policy. As a result, lift-truck operations should consider the return policy as a default with the traversal policy employed only at low pick densities. Furthermore, while prior research recommends against the Z-pick policy, this study shows that the Z-pick policy provides an adequate compromise between traversal and return. Thus, for managers seeking a single policy applicable across all pick densities, the Z-pick presents a viable option.

Conclusion

Ordering picking with lift trucks in a wide aisle warehouse represents a complex problem, often managed through the use of simple heuristics (De Koster, Le-Duc, and Roodbergen 2007). The updated Z-pick heuristic presents an alternative to a traversal policy that forces inefficient aisle crossings at high pick densities and the return policy that results in pickers passing multiple storage locations unnecessarily, especially at low pick densities. While the study presents an alternative formulation and models realistic warehouse operations, the work is not without limitations.

First, despite our efforts to model true-to-life lift-truck movement, some simplifying assumptions remained necessary. Maintaining exact acceleration, deceleration, and maximum speeds removed some potential variance as lift-truck operators reflect varying levels of comfort and expertise. Similarly, a set crossover time and turnaround time at the end of an aisle remove the possibility of traffic differences within the warehouse. Future simulations that vary these parameter values would uncover potential influences beyond the simple act of crossing an aisle, providing greater insight for managers and researchers alike. Second, while the research uncovered a trend and region of indifference separating the traversal and return policies, the simulation and Z-pick heuristic would not accommodate pick densities below 7 percent, removing the most extreme cases from consideration. As the Z-pick and traversal policies provided statistically similar results at low pick densities, an updated string length parameter for extremely low pick densities may prove even more beneficial for the Z-pick heuristic.

Beyond limitations, the research also provides several avenues for future research and discussion. For example, while the simulation employed a uniform random distribution, many warehousing operations slot their items differently. Thus, future research should examine alternative pick distributions and potentially earlier turnaround points for the return policy. Similarly, research combining lift truck and on-foot movements would likely provide a different region of indifference between the heuristics. Finally, given the influence of aisle crossing on routing policy performance, a more in-depth examination into the relationship between storage location width, aisle width, and pick density on order-picking policy selection is warranted.

Note: Disclosure: An early stage of this research (without the Z-pick) was presented at an academic conference and published in its proceedings.

Appendix A
The Z-Pick Policy Algorithm for the Simulation

The forklift routing problem represents a traveling salesman problem (TSP) in which an uncapacitated vehicle travels to a known set of locations at a minimum cost (Dantzig, Fulkerson, and Johnson 1954). Using Goetschalckx and Ratliff's (1988) notation, the problem includes a set number of items to be picked (*N*). Additionally, each rack contains *M* storage locations. $L_1, L_2,\ldots, L_n$ represent storage locations on the left side of the aisle while $R_1, R_2,\ldots, R_m$ denote locations on the right side of the aisle in ascending order from the entry points, L_0 and R_0 respectively. A variable, *k*, marks the side of the aisle on which the lift truck's current pick resides such that *k* equals either R or L and *!k* represents the opposite. Finally, *z* represents the crossing threshold, or the distance between picks on opposite sides of an aisle at which a crossover occurs.

```
Start Z-Pick
if $R_1 < L_1$ then
    $S \leftarrow R_0; S \leftarrow S \cup R_1; k \leftarrow R$
end if
else
    $S \leftarrow L_0; S \leftarrow S \cup L_1; k \leftarrow L$
end else
while $|S| < N + 1$
    if $k_i - !k_{i+1} > z$ then
        $S \leftarrow S \cup !k_{i+1}; k \leftarrow !k$
    end if
    else
        $S \leftarrow S \cup k_{i+1}$
    end else
end while
$S \leftarrow S \cup k_{M+1}$
End Z-Pick
```

Appendix B
Simulated Picking Processes

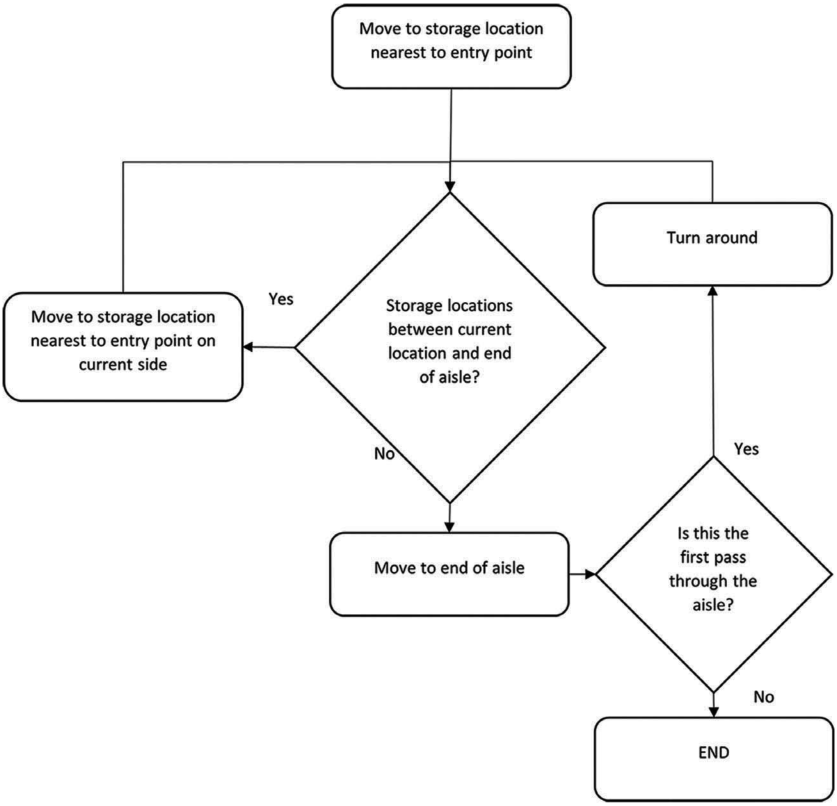

Figure B.1. Return Policy

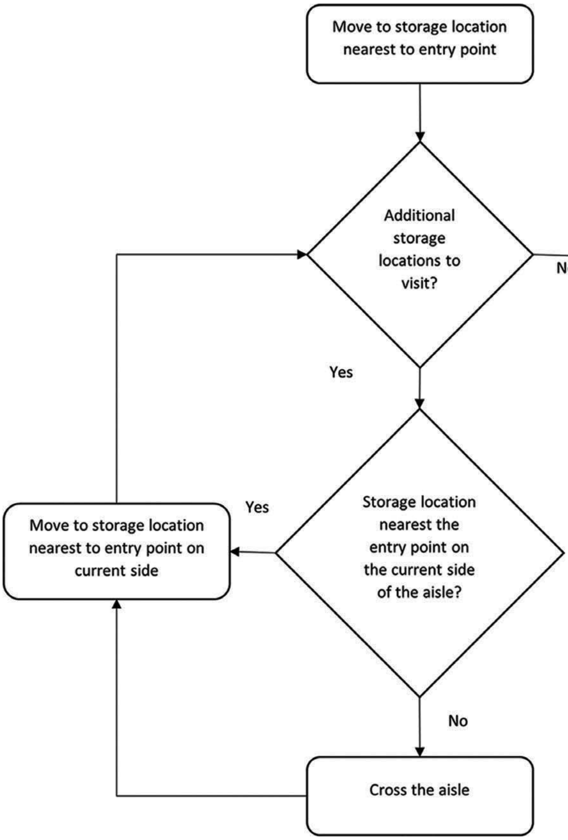

Figure B.2. Traversal Policy

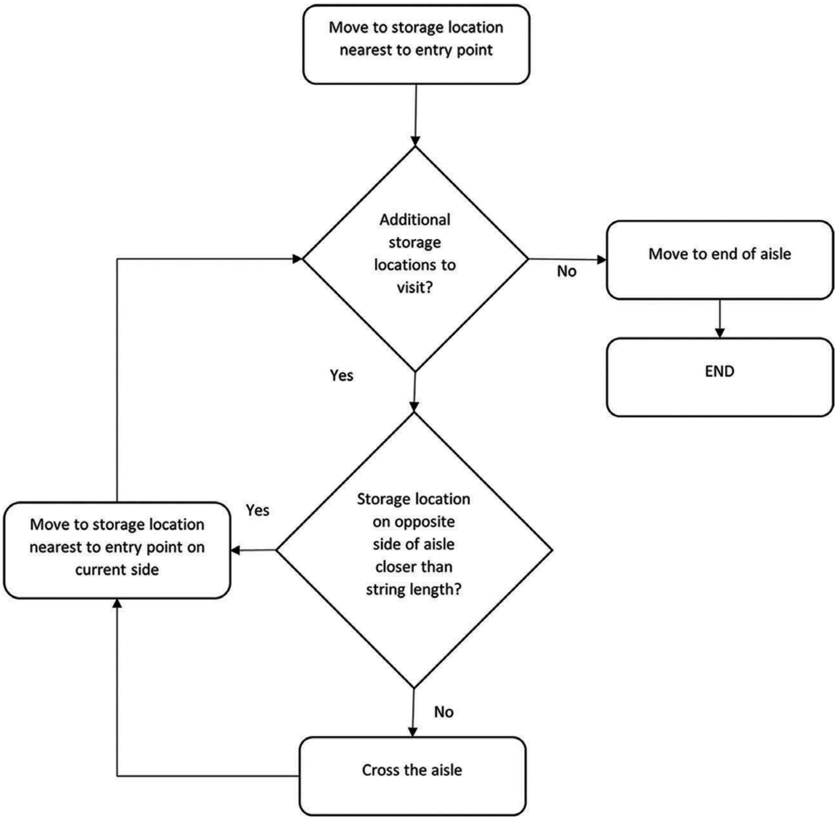

Figure B.3. Z-Pick Policy

Appendix C

Types of Movement Segments That Were Estimated

1. *Short distance forward linear movement*: From stop accelerate to v_{max} or below as distance permits, decelerate to stop. Example: from pos. 1 to pos. 5 (fig. 1).
2. *Long-distance forward linear movement*: From stop accelerate to v_{max}, maintain v_{max}, decelerate to stop. Example: from pos. 4 to pos. 49 (fig. 2).
3. *Short distance backward linear movement*: From stop accelerate to v_1 or below as distance permits, decelerate to stop. Example: from pos. 10 to pos. 8, if location 8 were on the pick list (fig. 1).

4. *Long distance backward linear movement*: From stop accelerate to v_1, maintain v_1, decelerate to stop. Example: from pos. 10 to pos. 6 (fig. 3).
5. *Aisle crossing with stop*: From stop accelerate to v_1, maintain v_1, decelerate to stop. Example: from pos. 5 to pos. 10 (fig. 1).
6. *Aisle crossing and continued forward linear movement with v_1 speed limit*: From stop accelerate to v_1, maintain v_1, decelerate to stop beyond aisle crossing. Examples: from pos. 6 to pos. 11 or from pos. 11 to pos. 18 (fig. 1).
7. *Aisle crossing and continued forward linear movement beyond v_1 speed limit*: From stop accelerate to v_1, maintain v_1 to end of aisle crossing, accelerate from v_1 to v_{max} or below as distance permits, decelerate to stop. Example: from pos. 6 to pos. 17, if location 17 were on the pick list (fig. 1).
8. *U-turn outside of the aisle from stopped position*: fixed time penalty (table 1).

Notes: v_{max} – maximum allowed speed (speed limit), v_1 – reduced speed for maneuvering. Items 1–7 are applicable to the traversal and Z-pick routing policies; items 1, 2 and 8—to the return policy.

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