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Minimization of metabolic energy expenditure in collaborative order picking

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Abstract

Order picking is one of the most repetitive, labor-intensive, and physically demanding operations in warehouses. Picking hundreds of orders daily requires high metabolic energy expenditure and is characterized by poor ergonomics posing high risks for musculoskeletal disorders. In traditional order picking, the order picker walks around racks in a warehouse throughout the day. Alternatively, it is aimed at minimizing inefficient time and musculoskeletal strains with ride-on order picking by allowing the order picker to stand on an operator's platform of an order-picking truck and ride the truck between stop locations. However, the order picker must step down from the platform at each stop location and step up onto the platform before riding the truck to the next stop location. Therefore, riding the truck with frequent stops leads to more metabolic energy expenditure and musculoskeletal disorders than walking, although it is faster. Benefiting advantages of both traditional and ride-on order picking, a relatively new order picking truck (collaborative order picking truck) is deployed in warehouses to reduce inefficient walking time and ergonomic riding disorders. In collaborative order picking, the order picker can walk from a stop location directly to the next pick location while the truck moves to the next stop location autonomously or ride the truck to the next stop location in case of having a large distance between stop locations. This paper develops an optimization model to minimize total metabolic energy expenditure in collaborative order picking by finding the shortest route and the best collaboration decision (walk or ride). Based on the Monte Carlo simulation, the metabolic energy expenditure with collaborative order picking is analyzed. Our results indicate metabolic energy savings with collaborative order picking up to 200% and 83% compared to traditional and ride-on order picking, respectively.

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Keywords: Order picking; Collaborative Robot; Optimal Routing; Ergonomics; Metabolic Energy Expenditure;

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1. Introduction

Order picking is one of the most critical operations in warehouses to retrieve customers' orders from storage locations in time [1], which is confirmed to be one of the most physically demanding and time-consuming operations in warehouses [2]. In addition to physical and temporal constraints, increasing labor costs compels companies to increase the productivity of order picking operations. Therefore, order pickers are pressured to handle more orders in a shorter time frame [3-4]. Accordingly, order picking operations are intensively studied in the literature by focusing mainly on travel time minimization, hence the maximization of order picking productivity [5-6]. However, ergonomics is relatively less mentioned in academic studies [7] even though order pickers are exposed to high ergonomic disorders due to abnormal postures, excessive force, and task repetition [6-7]. Moreover, operational models did not include human factors sufficiently [10]. Apparently, ignoring ergonomics in order picking operations results in an incomplete representation of real-world practice [1] and leads to the most common occupational disease for order pickers, musculoskeletal disorders [11].

Despite technological advances, traditional order picking (TOP) is still significantly used in small- or middle-sized warehouses [10-12], which is characterized by walking long distances (see Fig. 1.a). Even though walking is one of the best exercises for physical and mental health, prolonged walking is associated with musculoskeletal discomfort and injuries [14]. Moreover, the throughput of the picking operations is constrained by the walking speed of the order picker, resulting in inefficient time.

Responding to physical/temporal constraints and increasing labor costs, companies tend to use ride-on order picking (ROP) by extending the speed limit to riding, which is faster than walking (see Fig. 1.b). Therefore, the order picker can travel faster large distances between stop locations. Note that each pick location has a corresponding stop location for the truck at the center of each picking aisle. However, riding leads to more Metabolic Energy Expenditure (MEE) and musculoskeletal disorders because the order picker must step down/up from/onto the platform at each stop location, which is approximately 1,200 times per shift [15]. Therefore, picking faster with ROP may lead to more ergonomic disorders than walking, especially for tours with frequent stops.



(a)



(b)

Fig. 1. (a) Traditional order-picking [16]; (b) ride-on order-picking [17].

Recently, collaborative order picking (COP) has been introduced to simultaneously reduce the inefficient time for walking (see Fig. 2.a) and ergonomic disorders for riding (see Fig. 2.b). The order picker can walk to the next pick location while the collaborative order-picking truck moves autonomously to the next stop location or ride the truck.

Therefore, the order picker can freely switch between walking to minimize ergonomic riding disorders and riding to reduce inefficient walking time. This raises our research question when the order picker walks or rides the collaborative order-picking truck. As walking requires less MEE than riding and riding is faster than walking, the decision can be made based on both ergonomic and temporal perspectives. Unlike early studies, this paper mainly focuses on the ergonomic perspective of the problem. By doing so, the MEE with COP is calculated for an order picker. Starting from an Input/Output (I/O) point, the truck visits all stop locations in a pick list. After picking all items in the pick list, the order picker drops the pallet or roll cage at the I/O point and gets another pallet or roll cage to collect items in another pick list. Note that walking is only allowed in picking aisles, and the order picker is forced to ride the truck in cross aisles for safety reasons. Therefore, a significant penalty is applied for walking between picking aisles.

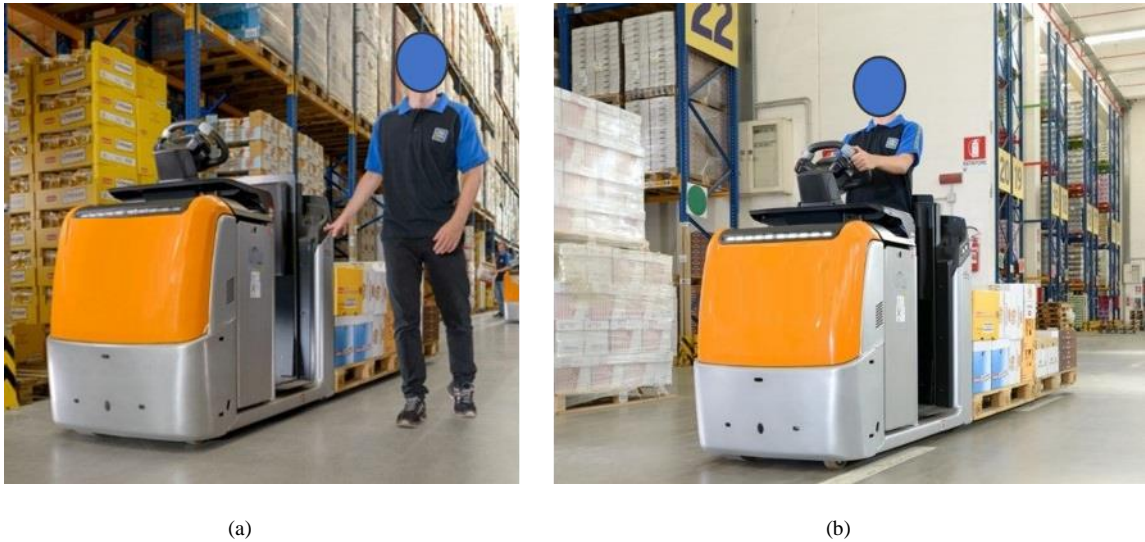
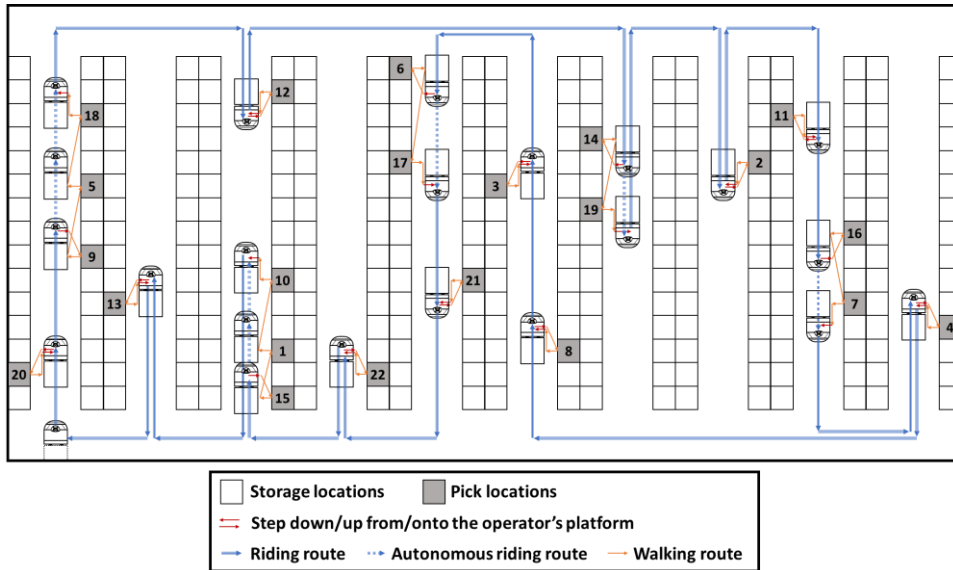


Fig. 2. Collaborative order-picking with (a) walking and (b) riding [18].

As shown in Fig. 3, the order picker starts from the I/O point located on the left corner of the warehouse and rides the truck directly to the first stop location (Stop Location 20), where the pallet or roll cage of the truck coincides with Pick Location 20 to minimize the handling time. After stopping the truck at Stop Location 20, the order picker steps down from the operator's platform and walks to the exact pick location (Pick Location 20) by following a Euclidian distance. Before walking back to Stop Location 20, s/he picks the item in the pick list. Afterward, s/he drops the item into the pallet or roll cage.

Depending on the distance between Stop Locations 20 and 9, the order picker may walk to Pick Location 9 or ride the truck to Stop Location 9. With the given parameter values in Fig. 3, the order picker rides the truck to Stop Location 9. Therefore, s/he steps onto the operator's platform of the collaborative order-picking truck at Stop Location 20 and rides the truck to Stop Location 9 while standing on the platform. After completing the order-picking operation, the order-picker decides to walk directly to Pick Location 5 using a Euclidean distance while the truck moves autonomously to Stop Location 5. Repeating this process for each pick location, the tour terminates after collecting all items. Eventually, the order picker drops the pallet or roll cage to the I/O point and takes another empty pallet or roll cage to collect items on the following pick list.



It can be observed in Fig. 3 that the visiting sequence of pick locations does not match with the pick list number; hence, the visiting sequence to collect all items must be determined. Therefore, we develop an optimization model to

Fig. 3. An illustrative example of COP with 22 pick locations in a 10-aisle warehouse.

minimize the total MEE by determining the shortest route and best collaboration decision (walk or ride). Based on the Monte Carlo simulation, we test different pick-list sizes and present the intractability of the optimization model for middle- or large-sized instances. Moreover, we implement the dynamic programming approach proposed by [19] for middle- or large-sized problems. Eventually, we report the improvement in MEE with COP for different pick list sizes compared to TOP and ROP.

We review the order picking problem literature by concentrating specifically on ergonomic problems in Section 2. Section 3 includes optimization model, energy expenditure calculations and solution approach to find the optimal collaboration strategy. Section 4 provides computational results. The last section serves as a summary of the paper and offers recommendations for future research.

2. Literature Review

Order-picking literature mainly focuses on routing, layout design, storage assignment, order batching, and zoning problems by only considering temporal or economic values rather than ergonomic values, which are mentioned very infrequently [13]. Limiting our focus on ergonomic problems in order picking, we address interested readers in order-picking problems to review papers [10, 19, 20].

Biomechanical models are used to analyze the effect of physical activities on the musculoskeletal system [21]. [22] proposed an algorithm to evaluate the biomechanical stresses of manual materials handling jobs. [23] proposed a metabolic rate prediction model to estimate the metabolic rates of manual material handling jobs by considering the characteristic of a worker and the description of the material handling job. [24] studied the cognitive ergonomics of order-picking operations and investigated the effect of color, position, address information, and shelf coding on product recognition and acquisition time.

[25] developed an interactive ergonomic evaluation system based on the order picker's assessment of video recordings. [26] developed heuristic algorithms to determine the storage locations of products by including strategies

to increase the accuracy of picks and reduce ergonomic problems. [27] evaluated order-picking operations regarding time consumption and ergonomic risks based on video recordings and physiological measurements. [28] conducted a laboratory experiment to compare the effects of ergonomic training with the lifting equation of the National Institute for Occupational Safety and Health (NIOSH). [29] identified ergonomic risks for different grocery warehouses and suggested intervention policies to reduce exposure to ergonomic problems. [30] used the verbal protocol method to investigate the thoughts of order pickers during and after an order picking operation. [31] proposed a scheduling framework for order picking operations, including physical and cognitive order-picker characteristics in a semi-automated order picking warehouse.

[32] compared two handle designs for pallet jacks based on usability, comfort, and biomechanical and physiological factors. [33] investigated alternative learning curves to assess learning effects on order-picking operations. [34] studied the effects of horizontal/vertical bin locations, bin angle, and hand usage on arm movements. [13] proposed a framework to integrate human factors into order-picking planning models. Evaluating human factors in order-picking operations, [35] provided a guideline for the usage of qualitative methods. Considering energy expenditure and operation time, [36] developed a multi-objective method and analyzed an integrated storage assignment approach. [37] proposed a heuristic algorithm to pick safely clustered items at each stop location and used a simulated annealing method to minimize total tour time. [20] reviewed the research literature on order-picking systems and discussed the integration of human factors in designing and managing order-picking systems. Converting ergonomic efforts to cost, [38] proposed a method to evaluate ergonomic factors in order picking operations under consideration of availability and rest allowance of order pickers. [39] developed a mathematical model to analyze different rack layout configurations by considering both economic and ergonomic performance measures. Integrating storage assignment and zoning problems, [8] developed an optimization to minimize the maximum ergonomic burden among order pickers.

[40] compared flat and tilted pallet containers using qualitative observation and Rapid Entire Body Assessment (REBA) methods. [41] described the usage of handheld scanners in order-picking operations to eliminate wrist motions. Considering the rotation of pallets, [42] developed a mathematical model to estimate the ergonomic and cost aspects of order picking operations. [43] explored the impact of head-worn displays and user interface designs in order picking operations. [44] calculated energy expenditure for order picking operations in three different layout configurations in addition to developing cost functions. Determining optimal layout and storage assignments, [45] developed two mixed integer programming models to minimize the total travel distance and total ergonomic strain for order pickers. [45] studied the layout configuration and item allocation problems with the objective of either minimizing total tour distance or total ergonomic strains.

[46] investigated the impact of technological items on order pickers' health. Decomposing the order picking operation into four activity levels, [47] proposed a technical method including activity information to evaluate the ergonomic risk for order pickers. [48] compared two order-picking systems based on average physical activity. [49] evaluated the impact of a smart workwear system on postural exposure.

[50] investigated the relationship between the positive effect of using digital technologies and the intensification of order-picking operations. [51] developed a heuristic approach to solve joint order batching and scheduling problems by considering the fatiguing effect of order-picking operations. [52] reviewed the literature and conducted interviews to identify human factors resulting in quality issues in order picking operations. Considering the time, energy expenditure, and health risks in order picking operations, [53] developed a multi-objective optimization model for the storage assignment problem. [54] proposed a method to use context information in an activity recognition model. [55] presented a safe and flexible mechatronic interface for the integration of generic mobile robots and collaborative robots. [56] explored the kinematics of nine workers' back and shoulder movements by using an optical motion capture system. Proposing a difficulty ranking system, [57] introduced a new aisle layout and a storage assignment strategy concerning ergonomic criteria. [58] assessed ergonomic risks of warehouse workers based on a marker-based motion capture system. [59] proposed a structured ergonomic evaluation methodology to assess the discomfort levels and risk factors at manual material handling tasks. [60] proposed a

method for the biomechanical analysis of manual material handling tasks. [61] conducted a field study to investigate the familiarization period for a passive shoulder exoskeleton and shows its benefit to material handling workers.

The literature review concludes that our study differs from the order-picking problem literature by focusing on ergonomic values in COP rather than economic or temporal values. Unlike earlier studies, we determine the optimal route and best collaboration strategy (walking or riding) to minimize the total MEE.

3. Model Description

To determine the shortest route and best collaboration strategy, a variant of the traveling salesman problem is formulated using MEE formulations given by [23] and [62]. The order picker can travel in both directions and change direction in picking aisles. We do not include MEE to pick items from racks since it does not affect the decision for the optimal route and the best collaboration strategy.

3.1. Notation

The following notation is used to develop the optimization model.

Nomenclature	
<u>Set (indices)</u>	
$P(p, q)$	the set for pick locations with indices p and q (0 for the I/O point)
<u>Parameters</u>	
M	a relatively large number
L	the length of each aisle (m)
d_a	distance between centres of two adjacent aisles (m)
d_o	distance from the operator's platform to the centre of a pallet or roll cage
v	the width of a picking- or cross-aisle (m)
d_e	Euclidian distance from the operator's platform to a pick location ($d_e = [d_o^2 + (0.5v)^2]^{1/2}$, m)
b_w	body weight (kg)
g	grade of the ground surface (%)
s_w	walking speed (m/s)
s_R	riding speed (m/s)
E_{st}	MEE for standing ($E_{st} = 0.023*b_w$, Kcal/min)
E_w	MEE for walking ($E_w = 0.01*[51+2.54*b_w+s_w^2+0.379*b_w*g*s_w]$, Kcal/min)
E_{sp}^w	MEE for stepping down/up from/onto the operator's platform ($E_{sp} = 0.00285*b_w$, Kcal/step)
E_{pq}^w	total MEE for walking between pick locations p and q
E_{pq}^R	total MEE for riding between pick locations p and q
<u>Decision Variables</u>	
w_{pq}	1, walking between pick locations p and q ; 0, otherwise
r_{pq}	1, riding the truck between pick locations p and q ; 0, otherwise
u_p	sequence of pick locations visited

3.2. Optimization Model

The optimization model can be stated as follows:

Minimize

$$\sum_{p \in P \cup \{0\}} \sum_{q \in P \cup \{0\}} [E_{pq}^W w_{pq} + E_{pq}^R r_{pq}] \tag{1}$$

Subject to:

$$\sum_{p \in P \cup \{0\}} [w_{pq} + r_{pq}] = 1 \quad \forall q \in P \cup \{0\} \tag{2}$$

$$\sum_{q \in P \cup \{0\}} [w_{pq} + r_{pq}] = 1 \quad \forall p \in P \cup \{0\} \tag{3}$$

$$u_p - u_q + (|P| + 1)(w_{pq} + r_{pq}) \leq |P| \quad \forall p \in P, \forall q \neq p \in P \tag{4}$$

$$1 < u_p < |P| \quad \forall p \in P \tag{5}$$

$$w_{pq} \in \{0, 1\} \quad \forall p \in P \cup \{0\}, \forall q \in P \cup \{0\} \tag{6}$$

$$r_{pq} \in \{0, 1\} \quad \forall p \in P \cup \{0\}, \forall q \in P \cup \{0\} \tag{7}$$

$$u_p \in \mathbb{Z}^+ \quad \forall p \in P \tag{8}$$

Objective function (1) minimizes the MEE for each order-picking route by determining the best route and collaboration strategy. Constraint (2) enforces that there is exactly one arrival to one pick location from other pick locations. Constraint (3) ensures there is only one departure from a pick location. Constraints (4) and (5) force the optimization model to have a single route covering all pick locations [63]. Finally, binary restrictions on decision variables w_{pq} , r_{pq} are imposed, and the integrality of the decision variable u_p is ensured (Constraints 6-8).

3.3. Metabolic Energy Expenditure Calculations

This section provides an algorithm to calculate the MEE between pick locations p and q . As a result, it establishes an energy expenditure matrix that can be employed in the optimization model. Assuming the leftmost aisle is the first aisle, aisles are numbered sequentially through to the rightmost aisle from the reader's point of view and denoted by a_p or a_q . Similarly, we let l_p or l_q represent the distance of storage location p or q from the bottom of each picking aisle (namely, storage location number). Then, each pick location $p \in P$ or $q \in P$ can be identified by a tuple of $\langle a_p, l_p \rangle \in \{a_0, a_1, \dots, a_{|P|}\} \times \{l_0, l_1, \dots, l_{|P|}\}$ or $\langle a_q, l_q \rangle \in \{a_0, a_1, \dots, a_{|P|}\} \times \{l_0, l_1, \dots, l_{|P|}\}$. Note that $p = 0$ or $q = 0$ corresponds to the tuple of $\langle a_0, l_0 \rangle$, representing the I/O point. Algorithm 1 is developed to calculate the MEE for walking or riding. Depending on the TOP, ROP, and COP, E_{pq}^W , E_{pq}^R or $\min [E_{pq}^W, E_{pq}^R]$ are used in calculations.

Algorithm 1. MEE Calculations for walking or riding.

```

for  $p = 0:|P|$ 
  for  $q = 0:|P|$ 
    if  $p = q$  % no travel from pick location  $p$  to pick location  $q$  when  $p = q$ 
       $E_{pq}^W = M$  and  $E_{pq}^R = M$ 
    else if  $p = 0$  % MEE from I/O point to any pick location
       $E_{pq}^W = (E_w + E_{st}) [d_a (a_q - 1) + l_q + v] / (60s_w)$  (for TOP);
       $E_{pq}^W = M$  (for COP);
       $E_{pq}^R = E_{st} [d_a (a_q - 1) + l_q + 0.5v] / (60s_R) + E_{sp} / 2 + (E_w + E_{st}) (d_e) / (60s_w)$ 
    else if  $q = 0$  % MEE from any pick location to I/O point
       $E_{pq}^W = (E_w + E_{st}) [d_a (a_p - 1) + l_p + v] / (60s_w)$ 

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 $E_{pq}^W = M$  (for COP);
 $E_{pq}^R = E_{st} [d_a (a_p - 1) + l_p + 0.5v] / (60s_R) + E_{sp} / 2 + (E_w + E_{st}) (d_o) / (60s_W)$ 
else if  $a_p = a_q$  % MEE when picks  $p$  and  $q$  are in the same aisle
  if  $l_i = l_j$  % no MEE for picking multiple items from the same location
     $E_{pq}^W = 0$  and  $E_{pq}^R = 0$ 
  else % MEE when picks  $p$  and  $q$  are in the same aisle, but in different locations
     $E_{pq}^W = (E_w + E_{st}) [|l_p - l_q| + v] / (60s_W)$  (for TOP);
     $E_{pq}^W = (E_w + E_{st}) \{[(l_p - l_q)^2 + (0.5v)^2]^{1/2} + 0.5v\} / (60s_W)$  (for COP);
     $E_{pq}^R = E_{st} [|l_p - l_q|] / (60s_R) + E_{sp} + (E_w + E_{st})(0.5v + d_o + d_c) / (60s_W)$ ;
  end
else if  $a_p \neq a_q$  % travel distance when picks  $p$  and  $q$  are not in the same aisle
   $E_{pq}^W = \min\{(E_w + E_{st}) [2L - l_p - l_q + d_a |a_p - a_q| + 2v] / (60s_W), (E_w + E_{st}) [l_p + l_q + d_a |a_p - a_q| + 2v] / (60s_W)\}$ 
   $E_{pq}^W = M$  (for COP);
   $E_{pq}^R = \min\{E_{st} [2L - l_p - l_q + d_a |a_p - a_q| + v] / (60s_R) + E_{sp} + (E_w + E_{st}) (0.5v + d_o + d_c) / (60s_W),$ 
     $E_{st} [l_p + l_q + d_a |a_p - a_q| + v] / (60s_R) + E_{sp} + (E_w + E_{st}) (0.5v + d_o + d_c) / (60s_W)\}$ 
else % other cases
   $E_{pq}^W = M$  and  $E_{pq}^R = M$ 
end
end
end
end

```

3.4. Solution Approach

The optimization model is coded in MATLAB and solved by using Application Programming Interface (API) with Gurobi Optimizer version 9.5.2 build v9.5.2rc0 (win64). The model is run on 8GB RAM with a 3.60GHz Intel® Core™ i7-4790 processor. The time limit parameter is set to 7200 seconds (2 hours), and the solution performance is summarized in Table 1. As shown, increasing the pick list size increases the solution time. Moreover, the solution is not obtained in the given time frame for middle- and large-sized problems.

Table 1. Solution time (seconds).

List Size	Samples										Avg (s)
	1	2	3	4	5	6	7	8	9	10	
5	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
10	1	1	1	1	1	1	1	1	1	1	1
15	4	2	2	2	1	5	2	8	2	1	3
20	16	5	8	8	6	11	10	14	18	9	11
25	21	22	69	9	41	40	10	77	19	37	34
30	146	154	92	22	88	309	15	78	20	94	102
35	779	68	145	142	434	2019	755	4222	---	1818	---
40	449	1093	830	2614	1733	2598	820	2277	2635	394	1544
45	---	1285	2026	---	---	---	1676	---	1414	826	---
50	---	---	4763	---	---	---	---	1416	---	6639	---
55	---	---	---	---	---	---	---	3152	---	---	---

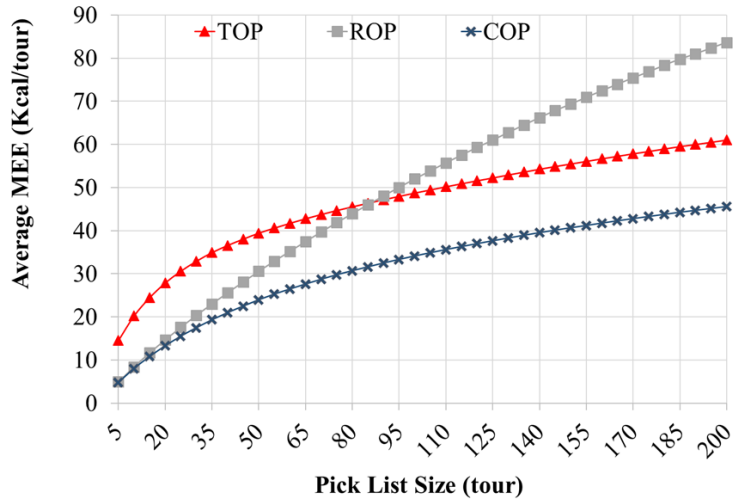


Fig. 4. Improvement in MEE for TOP, ROP, and COP.

Because of solution intractability for middle- and large-sized problems, we implement the dynamic programming approach proposed by Ratliff & Rosenthal [19]. The solution results given in the following section are generated by

using the dynamic programming approach. The maximum solution time for any pick list size is less than one minute.

4. Computational Results

In this section, we compare the performances of TOP and ROP with COP for different pick list sizes. Based on actual warehouse dimensions, the following parameter values are used. There are 10 aisles, each with a length of 25 m. The width of a picking- or cross-aisle is 2.7m. Considering a pallet size of 1.2m, the distance between the centerlines of two adjacent picking aisles is 5.3m, including side-to-side clearance between pallets. The number of pick list sizes ranges from 5 picks to 200 picks, with an increase of 5. Therefore, 40 different pick list sizes are tested. The average walking and riding speeds are 0.7m/s and 2.5 m/s, respectively. Considering only one pallet or roll cage is attached to the truck, the distance from the operator’s platform to the center of a pallet or roll cage is 1.1m. The body weight of the order-picker is assumed to be 80 kg.

We use Monte Carlo simulation to randomly generate aisle and storage location numbers of pick locations ($\langle a_p, l_p \rangle$). We replicate the solution 1000 times for each pick list size and take the average to generate Fig. 4. Note that each pick list is used three times to solve problems for TOP, ROP, and COP.

As shown in Fig. 4, COP outperforms TOP and ROP regardless of the pick list size. The relative MEE improvement of COP over TOP ranges between 33.7% and 199.6%, with an average value of 57.1%. Similarly, the relative improvement of COP over ROP varies between 1.9% and 83.2%, with an average value of 49.1%. Depending on the pick list size, ROP and TOP perform better than the other. With the given parameter values, ROP and TOP perform similarly when the pick list size varies between 85 and 90. TOP performs poorly for pick lists with fewer than 85 pick locations, whereas ROP performs well for small pick list sizes. Therefore, walking between rare pick locations or riding the truck with frequent stops leads to more MEE.

5. Conclusion and Recommendations

This paper investigates the metabolic energy expenditure of traditional, ride-on, and collaborative order picking. In traditional order picking, the order picker walks around racks in a warehouse throughout the day. Allowing the order picker to stand on an operator's platform of an order-picking truck, the order picker rides the truck between stop locations in ride-on order picking. However, the order picker must step down from the platform at each stop location and step up onto the platform before riding the truck to the next stop location. Taking advantage of both traditional and ride-on order picking, the order picker can switch between walking along and riding the truck in collaborative order picking. Therefore, further research is required to investigate the trade-off between walking and riding in terms of metabolic energy expenditure, as prolonged walking or frequent stepping down/up from/onto the truck can be associated with high metabolic energy expenditure.

We develop an optimization model to minimize the metabolic energy expenditure in collaborative order picking by finding the shortest route with the best collaboration decision (walk or ride). Moreover, we proposed an algorithm to calculate the metabolic energy expenditure between pick locations. Note that the algorithm is developed for the particular design provided. If different layout configurations are used, it will need to be adjusted accordingly. Comparing collaborative order picking with traditional and ride-on order picking, our results show a significant saving in metabolic energy expenditure. The traditional order picking is useful for large pick list sizes with frequent stops, whereas the ride-on order picking is beneficial for small-sized pick lists.

In this paper, we investigate a traditional warehouse layout. Non-traditional layouts can also be explored. Different routing or storage policies can also be investigated. The suggested algorithm is designed for a single-block layout. An algorithm tailored for two- or multi-block designs can be developed separately. Consideration of various shape factors (width-to-depth ratio) may lead to more metabolic energy savings.

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