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Human Energy Expenditure in High-Level Order Picking

Murat BİNİCİ[1,2*], Mehmet Mutlu YENİSEY[2]

[1]*Bitlis Eren University, Faculty of Engineering and Architecture, Bitlis, Türkiye*
[2]*Istanbul University-Cerrahpaşa, Faculty of Engineering, Istanbul, Türkiye*
(ORCID: 0000-0003-1814-438X) (ORCID: 0000-0002-4532-344X)

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Abstract
Order picking is one of the most significant components of the warehouse management. More than 50% of the cost incurred in warehouses is due to the order picking process. Although this process has mostly been considered within the framework of economic objectives, in recent years the ergonomic perspective has become increasingly visible. Order picking studies regarding ergonomic objectives have mostly focused on low-level order picking systems, but the human factor has been ignored in high-level order picking. In order to fill this gap, this study focuses on the order picking process of a single block high-level warehouse with a special focus on human factor. For this purpose, a capacity-constrained mathematical model based on order batching and routing for the minimization of human energy expenditure is proposed. In this three-dimensional (3D) warehouse system, the distances and travel times between locations were first determined using Manhattan distance-based Tchebychev formulas in order to calculate the human energy expenditure between order locations. Then, human energy matrices between order locations were created using human energy calculation formulas based on time and item weight. These matrices, which were created for three different randomly generated sample data sets, were used in the mathematical model solution and the optimum batches and routes were determined. In order to compare the results, First-come First-serve (FCFS) batching and S-shaped routing, which are simple and common batching and routing methods used in practice, were applied for the sample problem data sets and it was observed that the mathematical model gave better results.

1. Introduction

In today's world of intense competition, companies can achieve a solid competitive structure with the successful implementation of supply chain management and one of the most important components of the supply chain is warehouses [1]. More than 50% of the total cost incurred in a warehouse is due to the order picking process [2]. Order picking refers to the process by which orders are collected from warehouse locations and returned to the customer, and this process consists of labor-intensive and costly activities [3].

Various order picking systems are used in warehouses. The most common of these is the picker-to-parts order picking system. In this system, the order picker picks items from the order list by walking or driving an order picking vehicle. Moreover, this system is divided into low-level and high-level order picking. In low-level order picking, the order picker picks the items on the order list from low-level shelves in the warehouse where a person can comfortably reach. In high-level order picking, the order picker picks the items on the order picking list using order picking tools that can reach high shelf levels. In low-level order picking, only horizontal distance is considered, while in high-level order

*Corresponding author: *mbinici@beu.edu.tr*
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picking, horizontal and vertical distance calculations are used together [3]. Low-level warehouses can therefore be referred to as two-dimensional (2D) warehouses, while high-level warehouses can be referred to as three-dimensional (3D) warehouses [4]. The majority of order picking studies have focused on low-level warehouses, but studies on high-level warehouses, which provide efficiency in space utilization in warehouses, have been neglected [5,6].

In the order picking process, four different approaches have been developed to improve efficiency through the minimization of order picking time or travel distance [1]. The first one is to minimize the travel time by using a suitable order picking route. The second is the division of the warehouse into zones. Order pickers are assigned to these zones and only pick orders in their zone. The third approach is storage location assignment, i.e. assigning items to locations on the shelves within the warehouse. The fourth approach is the batching of orders. All of the batched orders are picked at once within their own batch. Among all these methods, the most important approaches are storage location assignment, order batching and routing [1]. Batching has a great impact on reducing the order picking time [2], and it can improve system performance [7]. Routing also has a great impact on optimizing the order picking system [8].

Although the order picking process is generally addressed by considering economic objectives such as time and distance minimization, human factor is also one of the important issues to be studied in this field [9]. The necessity of including the human factor in the order picking process has been emphasized in recent studies [6,10]. Despite of the fact that technological developments related to the automation of warehouse processes have increased in recent years due to Industry 4.0, humans are still at the center of this process [11]. However, the human factor has been ignored in most order picking studies [9]. By including ergonomic objectives related to the human factor in these studies, health risks can be minimized. This can reduce the loss of employees and absenteeism due to illness. In this way, both economic goals can be achieved and a positive contribution to the work-life balance of the employee can be achieved [9].

There are some studies regarding the human factor in order picking. In one of these, a human energy-based storage location assignment policy that minimizes total order picking time and human energy expenditure in a low-level warehouse system were proposed [12]. A heuristic model is proposed to analyze the optimal rack design and storage location assignment policy for a low-level order picking system that takes into account order picking cost, human energy expenditure and worker posture [13]. In another storage location assignment study based on human energy expenditure, a low-level order picking system was considered and a mathematical model was proposed [14]. A simulation study was conducted for a low-level order picking system using hybrid order picker humans and robots, taking into account cost, efficiency and human energy expenditure, in order to determine the optimal storage location assignment policies [15]. In another study where economic and ergonomic objectives were used together, a two-stage methodology was presented to determine the storage location assignment policy in a low-level warehouse [16]. In a low-level order picking study in which a multi-objective linear programming model was proposed for the minimization of the order picking time, human energy expenditure and health risk, different scenarios were considered to determine the storage location assignment policy and optimum shelf locations [17].

Considering the studies in this field, there is no study that deals with the human factor in the batching and routing of high-level order picking. Therefore, in this study, in order to fill a gap in this field, human energy expenditure in high-level order picking is considered and a batching and routing based mathematical model minimizing human energy expenditure is proposed.

In the second part of the study, the warehouse and problem is defined. In the third section, the solution method is stated. While the implementation of the method and the results are given in the fourth section, the last two sections include discussion and conclusions respectively.

2. Warehouse and Problem Definition

The warehouse in this study is single block and high-level (Figure 1). The order picker starts its movement from the input/output (I/O) point. The I/O point is located at the bottom left corner of the warehouse [4, 18]. In total there are 10 rows of shelves from left to right. The first and last shelves are single rows and the other shelves are back to back. The shelves have a depth of 1 meter. Each row of shelves consists of 10 divisions and each division has 5 layers. There are 50 locations in a single row of shelves and the total number of locations in the warehouse is 500. In addition to the front and rear cross aisles, there are five picking aisles in the warehouse. Locations are numbered in sequence from 1 to 500, starting from the first floor of the shelf row on the far left of the warehouse to the fifth floor on the upper right corner of the shelf row on the far right. For example, the number 5 in Figure 1 refers to locations 1, 2, 3, 4 and 5 starting from the first floor to the 5th floor. The following number 10 refers to locations 6, 7, 8, 9 and 10 from the first floor to the fifth floor respectively. Of these, locations 1 and 6 are located on the first floor, locations 2 and 7 on the second floor, locations 3 and 8 on the third floor, locations 4 and 9 on the fourth floor and locations 5 and 10 on the fifth floor. For all other locations, the last digit of the location number corresponds to the floor number of the first 9 locations. Locations with the last digit ending in 0 indicate that they are on the fifth floor. The I/O point is at floor height and has a height of zero. The lengths of the warehouse are shown in Figure 1.

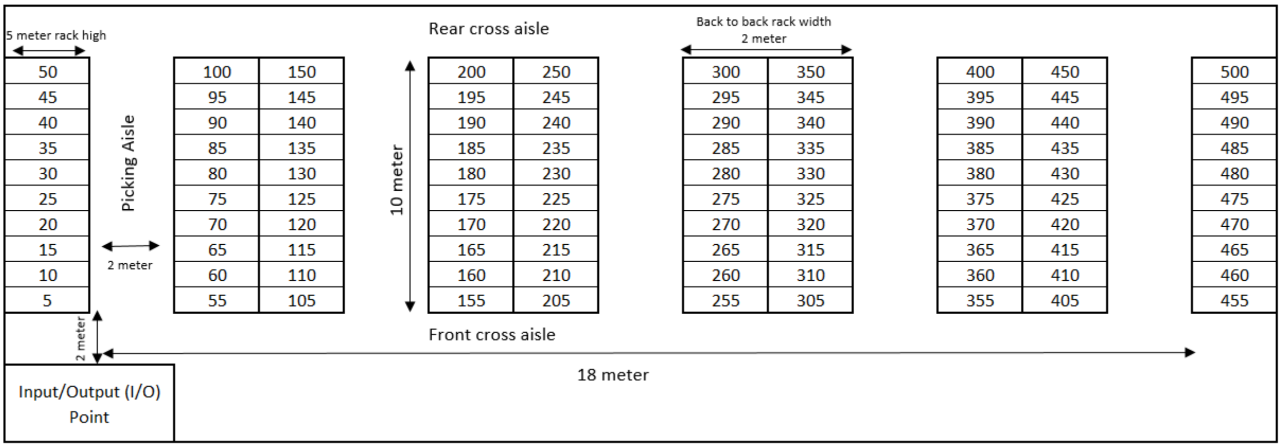


Figure 1. Top view of a single block and high-level warehouse

The horizontal and vertical speeds of the order picking vehicle are different, while the horizontal and vertical movements are simultaneous. No reference height when crossing the aisles is considered in this study. In other words, the movement from the height of the location in one aisle to the height of the location in the other aisle continues without interruption. The speed of the order picker when lifting and lowering, with or without load, is the same.

Each location has a single item type. Items have different weights. The maximum weight of an item is considered to be 20 kg [13]. The capacity of the order picker is determined on the basis of the number of items, which is 5 in this study.

Each order consists of a single item. Incoming orders will be picked by the order picker using the order picking vehicle. The number of orders to be picked is either the total number of orders reached in a given time interval or a predetermined target number of orders reached. Incoming orders are batched according to the capacity of the order picking vehicle and the order picking route is determined for each batch. The order picker expends energy during the order picking. This energy expenditure consists of both the energy expended when the order picker is not lifting any load in the order picker, i.e., when it is just standing while driving, and the energy expenditure that occurs when lifting items with a certain weight at the locations. The aim of this study is to batch and route incoming orders in a way that minimizes human energy expenditure.

3. Methodology

The overall objective of the batching and routing problem in order picking is to minimize the travel distance or time. The order picking routing problem can be modeled as a classical Steiner traveling salesman problem by computing an LxL matrix where i,j is the minimum travel distance or minimum travel time from storage location i to storage location j [4]. By adding batch capacity constraints to the routing problem, the batching and routing problem can be expressed as an integer programming model [1]. In this study, since human energy minimization will be performed, the human energy matrix LxL between locations will be used instead of distance or time between locations.

In this study, a mixed integer linear programming (MILP) mathematical model based on order batching and routing is proposed to minimize the human energy expended during the picking of orders from warehouse locations.

Assumptions:

- Each order contains one item.
- Each item has a weight and the maximum weight is 20 kg.
- Each location has only one item type and there are always items in the locations.

- The warehouse has a random location assignment policy. That is, items are randomly assigned to empty locations in the warehouse [19].
- Order picker capacity is expressed in terms of the number of items [1].
- The distance, time, and human energy expenditure between the locations are known in advance.
- Each tour starts from the I/O point and returns to the I/O point.
- Aisles are wide enough for two vehicles to pass through comfortably and there is no congestion.
- From the I/O point, the movement starts at zero height.
- There is no reference height at aisle entrances and exits.
- In aisle turns, the movement is linear and the turn angle is not considered.
- Horizontal and vertical speeds of the order picker vehicle are different and standard.
- The speed of the order picker is constant throughout the horizontal and vertical movements.
- The speeds of the order picker when lifting and lowering are the same and independent of the load.
- The order picker is standing on the vehicle while picking orders.
- The order picker is a male at the age of 30 and has a body weight of 75 kg [12].
- In all locations, the handling time of the order picker is the same and does not vary depending on the weights of items. It is assumed that the order picker carries the item during this time.

3.1. Notations

The indices, variables and parameters used in the mathematical model are explained in this section.

<u>Indicies:</u>
p: 1, 2,…..,P for locations.
l: 1, 2,…..,L for locations.
b: 1,2,.......,B for batches.

<u>Decision Variables:</u>
x_{bp}: 1 if location p is assigned to batch b, 0 otherwise.
y_{pl}^{b}: 1 if location p is immediately after location l in batch b, 0 otherwise.

<u>Parameters:</u>
C: Capacity of order picking truck vehicle (number of items)
G: Number of batches
S: Subset of set V
v_h: Horizontal speed of the order picker vehicle (m/s)
v_v: Vertical speed of the order picker vehicle (m/s)
t_{pl}: Travel time between locations p and l (sec)
h_l: Item handling time at location l (sec)
he_{pl}: Amount of human energy expended from location l to location p (kcal)
E_{stand}: Human energy expenditure of standing for 1 second (kcal/s)
BW: Order picker body weight (kg)
w_l: weight of the item at location l (kg)
ΔE: Energy to hold 1 kg for 1 second (kcal/s)

3.2. Mathematical Model

The mixed integer linear programming mathematical model based on batching and routing that minimizes human energy in order picking is as follows:

<u>Objective Function</u>:

$$OBJ_{min} = \sum_b^B \sum_p^P \sum_l^L y_{pl}^b * he_{pl} \quad (1)$$

<u>Constraints</u>:

$$\sum_p^P x_{bp} \leq C \qquad \forall b,\ \ p > 1 \quad (2)$$

$$\sum_{b=1}^B x_{bp} = 1 \qquad \forall p,\ \ p > 1 \quad (3)$$

$$\sum_{b=1}^B x_{bp} = G \qquad \forall p,\ \ p = 1 \quad (4)$$

$$\sum_l^L y_{pl}^b = x_{bp} \qquad \forall b, p,\ \ p \neq l \quad (5)$$

$$\sum_l^L y_{lp}^b = x_{bp} \qquad \forall b, p,\ \ p \neq l \quad (6)$$

$$\sum_{i,j \in S} y_{pl}^b \leq |S| - 1 \qquad \forall S \in V,\ \ p \neq l \quad (7)$$

$$x_{bp}, y_{pl}^b = \{0,1\} \qquad \forall b, p, l \quad (8)$$

Equation (1) gives the objective function and minimizes the human energy expenditure. Equation (2) is the capacity constraints of the order picking vehicle. The number of items picked in a single batch cannot exceed this capacity. According to Equation (3), each location is assigned to a batch, except for the I/O point represented by location number 1 in the solution of the model. Equation (4) states that each batch must have an I/O point. The number of batches (G) is the total number of orders divided by the capacity of the order picker (C). Equation (5) and Equation (6) state that in each batch b, there can be only one way from location p to location l and only one way from location l to location p. Equation (7) is the subtour eliminating constraints [20]. Equation (8) is 0-1 binary constraints.

3.3. Manhattan Distance-based Tchebychev Metrics and Travel Time Between Locations

The coordinates of the locations i and j of a 3D warehouse can be expressed as (x_i, y_i,z_i) and (x_j,

y_j,z_j) [4]. Figure 2 shows an example of the representation of the coordinates of locations i and j.

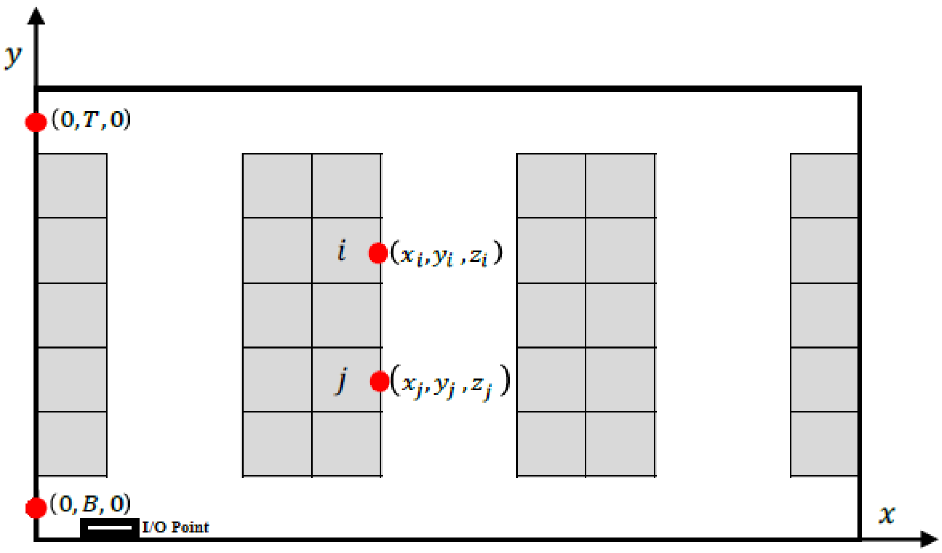


Figure 2. Top view of a single block high-level warehouse in X and Y Axis [4].

Points B and T are located on the y-axis and represent the upper and lower coordinates used to cross from one aisle to another, respectively. Also, x and y are the horizontal coordinates while z is the vertical coordinate. The minimum distance (d_{ij}) between locations i and j in the same aisle and the minimum distance from the I/O point to the locations within the warehouse are calculated by Equation (9). If the locaations are on different aisles, Equation (10) is used [4].

$$d_{ij} = |z_i - z_j| + |x_i - x_j| + |y_i - y_j| \tag{9}$$

$$d_{ij} = |z_i - z_j| + |x_i - x_j| + min\{|y_i - T| + |T - y_j|, |y_i - B| + |B - y_j|\} \tag{10}$$

Since the horizontal and vertical speeds of the order picking vehicles used in 3D warehouses are different, time calculation formula can be used instead of the distance formula. The travel time of a sequentially moving order picker between two locations in the same aisle and from the I/O point to the locations in the warehouse can be found using Equation (11). If the locations are on different aisles, Equation (12) is used [4].

$$t_{ij} = \frac{|y_i - y_j| + |x_i - x_j|}{v_h} + \frac{|z_i - z_j|}{v_v} \tag{11}$$

$$t_{ij} = \frac{|x_i - x_j|}{v_h} + min\left\{\frac{|y_i - T| + |T - y_j|}{v_h} + \frac{|z_i - z_j|}{v_v}, \frac{|y_i - B| + |B - y_j|}{v_h} + \frac{|z_i - z_j|}{v_v}\right\} \tag{12}$$

For order picking vehicles that perform simultaneous horizontal and vertical movements, the maximum travel time in horizontal and vertical movements is taken into account. Since the order picking vehicle considered in this study moves both horizontally and vertically simultaneously and at different speeds, the maximum travel time in horizontal and vertical movements can be found using the Tchebychev formula [4]. Equation (13) is used to calculate the travel time between locations within the same aisle and the travel time from the I/O point to a location within the warehouse, while the travel time between locations on different aisles can be found using Equation (14) [4].

$$t_{ij} = max\left\{\frac{|y_i - y_j| + |x_i - x_j|}{v_h}, \frac{|z_i - z_j|}{v_v}\right\} \tag{13}$$

$$t_{ij} = min\left\{\begin{matrix} max\left\{\frac{|y_i - T| + |T - y_j| + |x_i - x_j|}{v_h}, \frac{|z_i - z_j|}{v_v}\right\}, \\ max\left\{\frac{|y_i - B| + |B - y_j| + |x_i - x_j|}{v_h}, \frac{|z_i - z_j|}{v_v}\right\} \end{matrix}\right\} \tag{14}$$

3.4. Human Energy Expenditure

When calculating the human energy expenditure between two locations, both the time between locations and the weight of the items in the locations are taken into account. The order picker is standing on the order picking vehicle and therefore expends energy. Equation (15) gives the energy expended by a human in 1 second while standing depending on body weight, while Equation (16) gives the human energy caused by holding a load weighing w_p kg for 1 second [21]. Equation (17) gives the total human energy expenditure of travelling from location p to location l and putting the item from location l into the order picking vehicle.

$$E_{stand} = \frac{0.024 * BW}{60} (kcal/s) \quad (15)$$

$$\Delta E_l = \frac{0.062 * w_l}{60} (kcal/s) \quad (16)$$

$$he_{pl} = E_{stand} * t_{pl} + \Delta E_l * h_l \quad (17)$$

4. Implementations and Results

In this part of the study, three sample data sets were generated for the solution of the mathematical model. The proposed mathematical model for the problem was solved using the CPLEX solver in GAMS. Sample data sets of 5, 10 and 20 orders are shown in Table 1. Distance and human energy matrices were created for the locations of the orders. Equations (13), (14), (15), (16) and (17) were used to find the human energy expenditure between the locations. The average horizontal speed $\boldsymbol{v_h}$ of the order picking vehicle was taken as 3.33 m/s and the average vertical speed $\boldsymbol{v_v}$ as 0.40 m/s [22]. To compare the results of the mathematical model, FCFS batching and S-Shaped routing were applied using the same data sets.

Table 1. Number of orders and location numbers of orders

Sample data set	Number of orders	Location numbers of orders
1	5	443, 9, 22, 463, 367
2	10	196, 63, 192, 293, 311, 14, 202, 183, 447, 493
3	20	378, 194, 286, 249, 332, 63, 259, 4, 162, 215, 470, 117, 294, 166, 11, 110, 385, 483, 33, 305

4.1. Distance, Time and Human Energy Calculations

For the solution, it is first necessary to determine the distances between locations, and accordingly the time and energy expenditure. The solution will be explained in detail based on the sample data set 1. First, a 6x6 distance matrix consisting of 6 locations with I/O point 1 is created. The locations where the orders are located are numbered from 2 to 6 according to the arrival order. The distance matrix including horizontal and vertical distances calculated using Equations (9) and (10) is given in Table 2.

The calculation of the distance between locations 22 and 463, which are located on different aisles, is performed as follows: First, the x, y, z coordinates of both locations are found. Location 22 is on the second floor in the fourth shelf division of the first row of shelves in the picking aisle one. This location is at the zero meter according to the x coordinate, at the 7th meter according to the y coordinate, and the z coordinate, which expresses the shelf height, is at the 2nd meter. Location 463 is on the third floor in the third shelf division of the tenth shelf row in the fifth picking aisle. This location is at 18 meters according to the x coordinate, 5 meters according to the y coordinate and 3 meters according to the z coordinate. The x, y, z coordinates of locations 22 and 463 are (0,7,2) and (18,5,3) respectively. The coordinates of the crossing points B and T on the y-axis are 1 and 13 respectively. In this case, the shortest distances between locations 22 and 463 are calculated using Equation (10).

$$d_{22,463}(horizontal, vertical) = |x_{22} - x_{463}| + min\{|y_{22} - T| + |T - y_{463}|, |y_{22} - B| + |B - y_{463}|\}, |z_{22} - z_{463}|$$

$$= |0 - 18| + min\{|7 - 13| + |13 - 5|, |7 - 1| + |1 - 5|\}, |2 - 3|$$

$$= |-18| + min\{14, 10\}, |-1|$$

$$= 28, 1$$

In this case, the order picker will travel 28 meters horizontally and 1 meter vertically. Since the order picking vehicle moves horizontally and vertically simultaneously, the maximum of the horizontal and vertical travel times is found. For this reason, Equations (13) and (14) are used to calculate the travel times between the order locations. To find the travel time between the locations 22 and 463, Equation (14) is used since they are on different aisles.

Table 2. Horizontal and vertical distance matrix for the sample data set 1

Horizontal and Vertical Distances (meter)												
Locations	I/O (1)		443 (2)		9 (3)		22 (4)		463 (5)		367 (6)	
I/O (1)	0	0	27	3	4	4	7	2	23	3	20	2
443 (2)	27	3	0	0	27	1	24	1	8	0	11	1
9 (3)	4	4	27	1	0	0	3	2	25	1	22	2
22 (4)	7	2	24	1	3	2	0	0	28	1	25	0
463 (5)	23	3	8	0	25	1	28	1	0	0	13	1
367 (6)	20	2	11	1	22	2	25	0	13	1	0	0

$$t_{22,463} = min\left\{\begin{matrix} max\left\{\dfrac{|y_{22}-T|+|T-y_{463}|+|x_{22}-x_{463}|}{v_h}, \dfrac{|z_{22}-z_{463}|}{v_v}\right\}, \\ max\left\{\dfrac{|y_{22}-B|+|B-y_{463}|+|x_{22}-x_{463}|}{v_h}, \dfrac{|z_{22}-z_{463}|}{v_v}\right\} \end{matrix}\right\}$$

$$= min\left\{\begin{matrix} max\left\{\dfrac{|7-13|+|13-5|+|0-18|}{3.33}, \dfrac{|2-3|}{0.40}\right\}, \\ max\left\{\dfrac{|7-1|+|1-5|+|0-18|}{3.33}, \dfrac{|2-3|}{0.40}\right\} \end{matrix}\right\}$$

$$= min\left\{\begin{matrix} max\{9.6, 2.5\}, \\ max\{8.4, 2.5\} \end{matrix}\right\} = t_{22,463} = 8.4\ s$$

Table 3. Travel time matrix between the locations of the sample data set 1

Travel time between the order locations (s)						
	I/O (1)	443 (2)	9 (3)	22 (4)	463 (5)	367 (6)
I/O	0.0	8.1	10	5	7.5	6
443	8.1	0.0	8.1	7.2	2.4	3.3
9	10	8.1	0.0	5	7.5	6.6
22	5	7.2	5	0.0	8.4	7.5
463	7.5	2.4	7.5	8.4	0.0	3.9
367	6	3.3	6.6	7.5	3.9	0.0

Once the travel times between locations are determined, the human energy expenditure due to time can be found using Equations (15), (16) and (17). Since the travel times between locations given in Table 3 are the times when the order picker does not lift any item on the vehicle, only the energy caused by standing is calculated. In order to calculate the energy due to weight lifting at the locations, the weight of the items at these locations (w_l) and how long this weight is carried must be known (h_l) (Table 4). These weights are randomly assigned to the items with a maximum of 20 kg [13]. It was also assumed that the lifting time (h_l) of each location was 6 seconds and the body weight (BW) of the order picker was 75 kg [12]. In this case, an order picker going from location 22 to 463 expends energy both in the process of reaching location 463 and in the process of lifting the weight of the item (w_l= 10.2 kg) at this location. The total energy is the energy spent between these two locations. The matrix of human energy expenditure between order locations for the sample data set 1 is given in Table 5. Table 5 demonstrates that the human energy matrix based on the order locations is not symmetric. This is mainly due to the different weight of the items in each location. Even though the energy expenditure on both sides is the same during travel between any two locations, the human energy expenditure during lifting and placing the items in the order picking vehicle at order locations is not the same due to the different weight of the items in each location.

$$E_{stand} = \frac{0.024 * BW}{60} = \frac{0.024 * 75}{60} = 0.03\ (kcal/s)$$

$$\Delta E_{463} = \frac{0.062 * w_l}{60} = \frac{0.062 * 10.2}{60} = 0.01054\ (kcal/s)$$

$$he_{22,463} = E_{stand} * t_{22,463} + \Delta E_{463} * o_{463} = 0.03 * 8.4 + 0.01054 * 6 = 0.315\ kcal$$

Table 4. Item weights and handling times at locations

	I/O	443	9	22	463	367
w_l	0	17 kg	12.9 kg	17.4 kg	10.2 kg	19.5 kg
h_l	0 s	6 s	6 s	6 s	6 s	6 s

Table 5. Human energy matrix between the order locations of the sample data set 1

Locations	I/O (1)	443 (2)	9 (3)	22 (4)	463 (5)	367 (6)
I/O (1)	0	0.348	0.380	0.258	0.288	0.301
443 (2)	0.243	0	0.323	0.324	0.135	0.220
9 (3)	0.300	0.348	0	0.258	0.288	0.319
22 (4)	0.150	0.321	0.230	0	0.315	0.346
463 (5)	0.225	0.177	0.305	0.360	0	0.238
367 (6)	0.180	0.204	0.278	0.33	0.180	0

4.2. Solution of the Mathematical Model

GAMS optimization software was used to solve the mathematical model. Solutions for the three sample data sets were also performed. The item capacity of the order picking vehicle was set to 5 [23]. In each batch, travel starts from the I/O point and returns to the I/O point. Optimum batches, routes (by location number) and total human energy expenditures are given in Table 6. Also, the optimal route determined for the sample data set 1 is shown in Figure 3.

For the sample data set 1, only one batch was created and the picking sequence is specified in Table 6. The total human energy expenditure for the sample data set 1 was 1,353 kcal. In the analysis of the sample data set 2, the locations were divided into two batches and within each batch, the picking sequence for each batch takes place in Table 6. The minimum human energy expended for the sample data set 2 was 2,167 kcal. Finally, for the sample data set 3, the order locations were divided into four batches and picking sequence for each batch is given in Table 6. The minimum total human energy expenditure for the sample data set 3 was 4,253 kcal.

Table 6. Results of the mathematical model

Sample Data Set	Order Size	Batches and Routes	Total Energy Expenditure (kcal)	Throughput time (s)
1	5	Batch 1: I/O-22-9-463-443-367-I/O	1.353	59.2
2	10	Batch 1: I/O-196-192-183-14-63-I/O Batch 2: I/O-202-293-493-447-311-I/O	2.167	108.9
3	20	Batch 1: I/O-483-470-305-385-378-I/O Batch 2: I/O-194-249-294-332-286-I/O Batch 3: I/O-11-63-117-162-166-I/O Batch 4: I/O-33-4-110-215-259-I/O	4.253	224.3

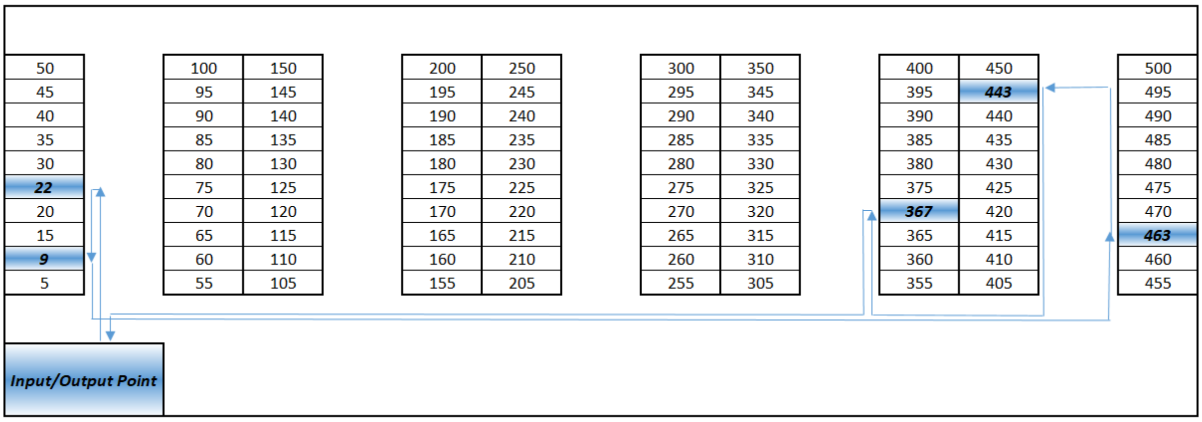
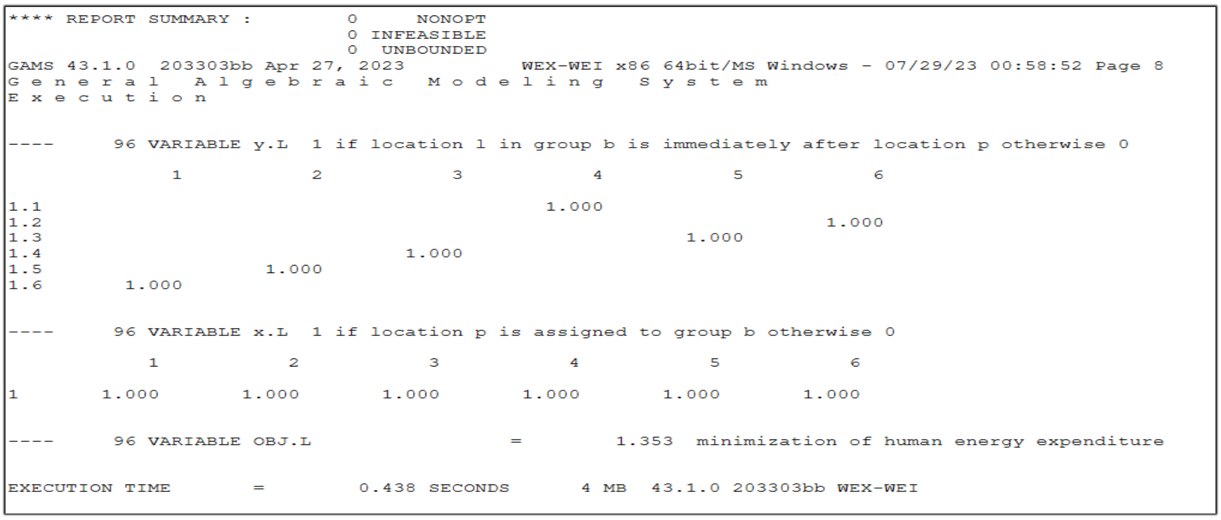


Figure 3. Optimum route for the sample data set 1



```
**** REPORT SUMMARY :          0      NONOPT
                               0 INFEASIBLE
                               0  UNBOUNDED
GAMS 43.1.0  203303bb Apr 27, 2023          WEX-WEI x86 64bit/MS Windows - 07/29/23 00:58:52 Page 8
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n


----      96 VARIABLE y.L  1 if location l in group b is immediately after location p otherwise 0

             1           2           3           4           5           6

1.1                                          1.000
1.2                                                                  1.000
1.3                                                      1.000
1.4                              1.000
1.5                  1.000
1.6      1.000


----      96 VARIABLE x.L  1 if location p is assigned to group b otherwise 0

           1           2           3           4           5           6

1      1.000       1.000       1.000       1.000       1.000       1.000


----      96 VARIABLE OBJ.L                  =        1.353  minimization of human energy expenditure


EXECUTION TIME       =        0.438 SECONDS      4 MB  43.1.0 203303bb WEX-WEI
```

Figure 4. GAMS screen display for the results of the sample data set 1

As can be seen in Figure 3, the order picker starts its movement from the I/O point at ground floor height and goes to location 22 on the second floor. From there, it moves along the same aisle to location 9 at the fourth floor height. The next travel point is location 463 and the order picker moves horizontally while simultaneously descending from the fourth floor to the third floor. From here the order picker travels to location 443 and does not move vertically but only horizontally. Travelling to location 367, where the last order in the order list is located, the order picker descends one floor to pick this order, which is located on the second floor. After all the orders have been picked, the order picker returns to the I/O point and at the same time moves down two floors to the ground floor.

4.3. Implementation of FCFS Batching and S-Shaped Routing

Warehouse managers prefer methods that are easier to implement for warehouse workers [6]. FCFS batching is a widely used method in practice and in many studies [3, 24, 25]. Similarly, the s-shaped (traversal) routing method is widely used in many warehouses due to its simplicity in terms of implementation [2]. For this reason, FCFS batching and s-shaped routing were applied to the same data sets to compare the results obtained with the mathematical model.

The capacity for each batch is 5 orders. If this number is not reached in the first aisle entered, the order picker crosses to the next aisle containing orders. If the capacity is reached in this aisle, the order picker returns to the I/O point to unload the orders. If there are still unpicked orders, the order picker moves to the nearest aisle containing orders and starts picking and returns to the I/O point when the capacity is reached.

FCFS batching and s-shaped routing results for the sample data sets are given in Table 7. In addition, the s-shaped route for the sample data set 1 is also shown in Figure 5.

Tablo 7. The results of FCFS batching ve S-shaped routing for the Sample Data Sets

Sample Data Set	Order Size	Batches and Routes	Total Human Energy Expenditure (kcal)	Throughput time (s)
1	5	Batch 1: I/O-9-22-367-463-443-I/O	1.602	67.5
2	10	Batch 1: I/O-63-196-192-293-311-I/O Batch 2: I/O-14-183-202-447-493-I/O	2.746	128.2
3	20	Batch 1: I/O-194-249-286-378-332-I/O Batch 2: I/O-4-63-162-259-215-I/O Batch 3: I/O-11-117-166-294-470-I/O Batch 4: I/O-33-110-305-385-483-I/O	5.327	260.1

The sample data set 1 consists of only one batch and the energy expenditure is 1,602 kcal as a result of s-shaped routing. The picking sequence for the Sample Data Set 1 is given in Table 7. In the batching and routing for the sample data set 2, the locations were divided into two batches and their picking sequence are given in Table 7. The total human energy expenditure of these two batches as a result of order picking was 2,746 kcal. Finally, as a result of FCFS batching and s-shaped routing for the sample data set 3, the order locations were divided into four batches and routes are given for each batch in Table 7. The total human energy expenditure for the sample data set 3 was 5,327 kcal.

Looking at Figure 5, in s-shaped routing, the order picker starts its movement by entering the first aisle closest to the I/O point, since it has orders in this aisle. While the horizontal movement towards location 9 continues, it also makes a four-meter upward movement from ground floor to the fourth floor towards this location, which is located on the fourth floor in its devision. After receiving the order at this location, it moves to location 22 on the second floor in the same picking aisle and makes a descending movement of two meters. The closest picking aisle where the order is located is the fourth picking aisle. Leaving the first picking aisle from the direction opposite to the direction it entered, it enters the fourth picking aisle and reaches location 367 on the second floor. There are two more orders in the last picking aisle. It goes to the first one, the closest location 463. Finally, after receiving the order at the last location 443, it exits from the direction it entered this aisle and returns to the I/O point.

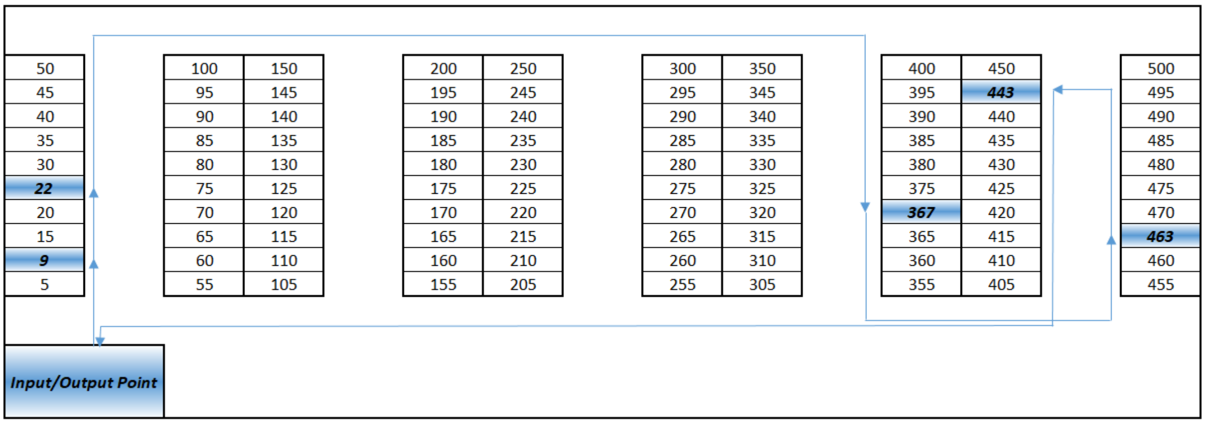


Figure 5. S-shaped route for the sample data set 1

5. Discussion

In this study, the order picking process in a sample single block high-level warehouse system was investigated from an ergonomic point of view. Firstly, human energy expenditures were calculated using the distance, time and human energy formulas. Then, human energy expenditure was minimized using a mathematical model based on order batching and routing for the three different sample data sets that were created for the analysis.

For the solution, three-dimensional (x, y, z) coordinates of the locations were determined to calculate the distances between the order locations in the high-level warehouse and the minimum distances were found. Since the high-level order picking vehicle travels simultaneously at different speeds horizontally and vertically, the travel times to the target locations were calculated. For this, Tchebychev formulas were used to find the maximum of the horizontal and vertical travel times. Since the human energy calculation depends on both the time between locations and the weights at the locations, the human energy matrices of the order locations were created using the standing and weight lifting human energy formulas. In order to compare the results of the mathematical model, FCFS batching and s-shaped routing methods, which are widely applied in warehouses, were also applied to the same sample data sets.

The mathematical model based on batching and routing was applied for the three different sample data sets and the results are given in Table 6. The results of FCFS and s-shaped routing method are given in Table 7. The results are also given comparatively in Table 8. Looking at Table 8, in all cases, both human energy expenditure and throughput time decreased when the human energy based mathematical model was used.

Table 8. Comparison of the results

Order Size	Batch Size	Batching and Routing	Total Human Energy Expenditure (kcal)	Throughput time (s)
5	1	FCFS and S-haped	1.602	67.5
		Human Energy Based Mathematical Model	1.353	59.2
10	2	FCFS and S-haped	2.746	128.2
		Human Energy Based Mathematical Model	2.167	108.9
20	4	FCFS and S-haped	5.327	260.1
		Human Energy Based Mathematical Model	4.253	224.3

In high-level warehouses, the distance, time and energy calculations differ from low-level warehouses. While low-level storages are 2D, high-level storages are 3D. For this reason, only horizontal movements are calculated in low-level order picking, while vertical movements should also be taken into account in high-level order picking. However, the fact that the horizontal and vertical speeds of the high-level order picking vehicles are different, but their movements are simultaneous, implies that special calculations are required. In the low-level warehouse, distance and time measurements between locations can be made on the (x, y) coordinate plane, while the high-level warehouse is similar to the (x, y, z) coordinate plane due to its 3D structure and calculations are made according to the three-dimensional coordinates of the locations. The use of Tchebychev formulas would be more accurate for 3D warehouses due to the simultaneous horizontal and vertical movement of the order picker. Because when moving from one location to another, the horizontal movement may end, but the vertical movement may still continue. Conversely, the destination may have been reached in the vertical, but the movement in the horizontal may still continue. For this reason, if order picking vehicles moving simultaneously are used in 3D warehouses, it would be a more accurate analysis to calculate time rather than distance. Since horizontal and vertical travel times may be different, using Tchebychev formulas that find the maximum of these times would be a better approach for high-level warehouses.

6. Conclusions and Suggestions

In this study, in which the human factor is considered in a single block high-level order picking, human energy expenditures based on the time between order locations and item weight were analyzed and the optimum human energy batches and routes were determined with the order batching and routing based mathematical model aiming at human energy minimization. Using three different data sets of 5, 10 and 20 orders, the mathematical model based on batching and routing gave better results than FCFS batching and s-shaped routing. The use of the Tchebychev formula to calculate the time between order locations for the order picker vehicle moving simultaneously horizontally and vertically in the high-level warehouse was significant in obtaining accurate results. In addition, using the (x, y, z) coordinate plane to find the distances between locations in high level (3D) warehouses has facilitated the achievement of accurate results.

In a future study to improve this work, meta-heuristic methods can be used for big data sets. Studies with more than one block and larger numbers of locations can also be conducted. Traffic congestion was not taken into account in this study, so a study that takes this into account can also be carried out. A study that takes into account the reference height at the aisle enters and exits can also be conducted. Finally, this study could be improved by taking into account the angle of rotation when crossing aisles.

Contributions of the authors

The authors confirm that the contribution is equally for this paper.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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