Volume 15 • Issue 4 • 2023

sciendo

received: 9 January 2023
accepted: 30 September 2023

pages: 12-24

Impact of human energy expenditure on order picking productivity: a Monte Carlo simulation study in a zone picking system

Nader A. Al Theeb
Omar Al-Araidah
Malik M. Al-Ali
Adnan I. Khudair

Nader A. Al Theeb

Jordan University of Science and Technology, Jordan
ORCID 0000-0003-1916-8076

Corresponding author:
naaltheeb@just.edu.jo

Omar Al-Araidah

Jordan University of Science and Technology, Jordan
ORCID 0000-0002-6871-139X

Malik M. Al-Ali

Jordan University of Science and Technology, Jordan

Adnan I. Khudair

Jordan University of Science and Technology, Jordan

ABSTRACT

This article aims to investigate the impact of allowable human energy expenditure (HEE) of order pickers on the throughput of workers in manual order zone picking systems MOP. The method used in this research is the Monte Carlo simulation, used while considering many human and job factors. The results showed that a worker's gender and an item's weight have little effect on the HEE. On the other hand, body weight, walking speed, distance travelled, and the targeted zone significantly impacted the HEE, rest allowance, and throughput. For example, male pickers at a weight of 75 kg can move up to speed to 1 m/s and pick up items weighing up to 5 kg without reaching the allowable HEE rate, equal to 4.3 kcal/min, and, thus, no rest is needed. Female pickers at a weight of 75 kg reach the allowable HEE rate, equal to 2.6 kcal/min, at a very low speed of approximately 0.1 m/s when picking up items up to 5 kg, and, thus, frequent rest is needed, which leads to low throughput. To increase the throughput of female pickers, they can be assigned to pick up lighter items. Utilising Monte Carlo simulation to evaluate the HEE in MOP while considering many factors.

KEY WORDS

human energy expenditure, manual order picking, Monte Carlo simulation, warehouse management

10.2478/emj-2023-0025

Introduction

Warehouses form a vital link in the supply chain, where all types of products can be temporarily stored until ordered. Upon receipt of an order, the picking system is required to retrieve the requested items from the storage areas manually or automatically. The main objective of the picking process is to fulfil customer orders, which is an expensive, labour-based process that sometimes consumes around 55 % of the whole warehouse operations. Thus, efficiently managing this process will lead to shorter times for fulfil-

Al Theeb, N. A., Al-Araidah, O., Al-Ali, M. M., & Khudair, A. I. (2023). Impact of human energy expenditure on order picking productivity: a Monte Carlo simulation study in a zone picking system. *Engineering Management in Production and Services, 15*(4), 12-24. doi: 10.2478/emj-2023-0025

ment, less cost, and better customer satisfaction. The process should be efficiently managed to achieve the best picking process efficiency. Management of the picking process includes the selection picker speed and the corresponding rest, the number of items per trip, the number of orders per trip, and the picking strategy selection.

There are different picking strategies. First, the zone-picking strategy has similar items stored in one section of the warehouse called a zone, and each picker is assigned to a zone to pick all ordered items from that zone. Second, discrete picking applies more to small warehouses. In this strategy, a picker is assigned to pick up all items in the same order from the whole warehouse. Third, batch picking has pickers assigned to pick the same item or a group of items in their vicinity for many orders. Fourth, wave picking lets pickers pick up only one item per trip. Lastly, two or more strategies can be applied together as a new strategy, such as assigning multiple orders to a picker in the batch strategy and storing the items in zones in the zone-picking strategy.

As explained, the picking process is labour-based and mostly manually performed utilising picking equipment. The Manual Order-Picking process (MOP) is a crucial sub-process within warehouses, logistics, and supply chain processes (Al-Araidah et al., 2021). Therefore, it is important for the MOP to be managed efficiently to enhance the system's performance (Petersen, 2002; Marmidis et al., 2008). According to Tompkins et al. (2010), the time taken for a picking trip is divided into five components: setup, travel, searching, picking, and others, with percentages of 10 %, 50 %, 20 %, 15 %, and 5 %, respectively. In addition to time, MOP consumes the physical energy of the picking workers. It is important to study the combined effect of time and energy expenditure on the MOP process and the order picker to maximise efficiency. Another important term related to the MOP process is throughput, which is a key performance indicator of the picking process and is influenced by the picking workers' time and human energy consumption. During the MOP, pickers are using one of the routing policies to move between the locations. Selecting a suitable policy plays a significant role in minimising the total distance travelled. Three of the most common policies are the strict order, first-come-first-served combined orders, and zone-picking orders (Petersen & Aase, 2004); the latter is the topic of this research.

The picking consumes pickers' energy, denoted as human energy expenditure (HEE). Many human and environmental factors affect the HEE, such as body mass, speed, item mass, warehouse temperature, etc. Many studies have investigated the HEE with respect to other factors, e.g., Ocobock (2016) studied the effect of temperature on the students' energy expenditure in different schools. Similarly, Westerterp (2017) studied the effect of body size and food intake on the HEE and rest requirements during some physical activities. The effect of obesity on the HEE has been studied by Pontzer et al. (2016) with respect to different physical activities. Picking operations have limited studies. For example, Grosse et al. (2015) have developed a framework based on a literature review to discover the opportunities for MOP improvements.

Different research techniques can be utilised to study the relationships between time and human energy consumption with respect to different human factors. One of these techniques is the Monte Carlo simulation (MCS). According to Harrison (2010), American scientists developed and used the MCS method for the nuclear field during World War II. This method was then used in various scientific fields, particularly intractable problems or experiments which are extremely expensive or time-consuming. MCS is used to predict output-based different inputs in uncertain situations by repeating the calculations many times.

This study investigates the effects of human and job factors on the well-being of order pickers and on the throughput of the MOP system. Studying these factors helps to better understand the MOP problem, which leads to the improvement of the process performance by increasing the throughput and minimising the fatigue level. This work considers many factors, such as the gender of the pickers, their body weights, picked item weights, and the speed of the pickers. The study uses metabolic energy expenditure equations from the literature to estimate the energy needs for every single task and uses Predetermined Time Standards System equations (PTSS) to estimate the time needed to achieve the work. Consequently, the HEE and throughput are found, and the moment when the pickers reach the maximum allowable HEE is determined. Based on this, rest requirements are determined for both male and female pickers.

As demonstrated in the next section, gaps in this field of research can be summarised as little consideration given by most studies to factors, such as environmental, worker body or picked items, to study the HEE. Additionally, they mainly use a few calculated scenarios to evaluate the results. This research will consider many worker-related factors and picked items to evaluate the HEE and throughput. Furthermore, MCS will be used to find the results, covering most of the possible picking-up scenarios.

The remainder of this article is arranged as follows. Section 2 represents the research related to this work. Section 3 fully describes the methodology, including the model used in this research to generate the results, the warehouse design, calculations of different factors and outputs, and methodology steps. Section 4 shows and discusses the obtained results. Finally, the major outcomes from this research are given in the Conclusions section.

1. Literature review

A close literature review showed several studies on the MOP, zone picking, and human energy expenditure (HEE). The following review concerns some articles that addressed the subjects separately or jointly.

Several researchers investigated the impact of various warehouse design factors on the performance of the MOP system. Such factors include the warehouse layout, the routing policy, the picking strategy, and the storage assignment (Saderova et al., 2020). Among others, Petersen et al. (2005) evaluated storage assignment strategies in terms of the time and distance that pickers need to accomplish orders. The authors studied the effect of the golden zone concept on time and distance (i.e., in item storage, the golden zone is the level between a picker's waist and shoulders). The results showed that the storage assignment strategies considering the golden zone significantly improve the time to fulfil the orders compared to strategies that ignore this concept. However, the use of the golden zone concept significantly increases the distance for the picker to travel. The study used the Monte Carlo simulation method to get these results. Ho and Liu (2005) studied the impact of converting a regular warehouse into a zone-picking warehouse on the total order-picking travel distance (TTD). The study used a group of algorithms and route planning to find the TTD improvements after converting into the zone-picking method. Roodbergen et al. (2008) developed an optimisation model to minimise the distance travelled inside a warehouse with the goal of providing a suitable layout structure; as found, the layout that resulted from the model was similar to the layout that resulted from the simulation packages, but with a better travel distance by utilising the S-shape routing. Parikh and Meller (2008) studied the problem of selecting between the batch-picking strategy and the zone-picking strategy. The authors developed a cost-estimation model to compare between these two strategies from the cost viewpoint. The proposed model considered several factors and their effect on the cost. The factors included the pick rate, picker blocking, workload imbalance, and sorting system requirements. Moreover, the authors presented a case study to show the effect of system throughput, order size, and item distribution in orders on selecting the picking strategy. Elbert and Müller (2017) studied the effect of the dimensions scale of warehouses on the time needed for MOP at a constant speed and body weight. The authors also considered the curves/turn manoeuvres in time and energy calculations. The study concluded that the time and energy costs could not be positively affected, particularly in small-scale warehouses.

Several researchers studied human energy for a wide range of household, personal, and work activities. An early study by Garg et al. (1978) proposed a new approach to estimating the metabolic energy for manual handling of materials. The authors assumed that each job, regardless of its complexity, can be divided into a set of simpler tasks. The study yielded a set of equations to calculate the estimated metabolic energy. Price (1990) investigated a number of methods for calculating RA for different types of jobs. The author developed a model to calculate RA for construction work, which can be used for other types of physical work. Since human energy is among the constraints that may impact the MOP system's performance, several authors took the HEE into account. Battini et al. (2016) developed a multi-objective model to accommodate ergonomics into the line balancing problem considering the human energy expenditure and consumed time. The study provided a predetermined motion energy system based on Garg et al. (1978) to predict the human energy expenditure considered as a level indicator of ergonomics. The authors validated the results with numerical examples. Çakıt (2016) used an energy expenditure prediction software to estimate the energy cost of manual waste collection works. The software used was built based on the equation by Garg et al. (1978). The study results showed a minuscule difference between energy costs predicted by the software and estimated by the equations from the literature. Calzavara et al. (2019a) considered different store layouts and then developed equations to determine the cost of picking and the HEE. Calzavara et al. (2019b) presented an optimisation model to optimise the time of working and time of resting for manual order-picking workers. The model is limited to activities involving the whole body. In the proposed model, the authors aimed to improve worker productivity by better scheduling their work and recovery time. Moreover, the model considers the rate and duration of activities in addition to the worker's physiological factors affecting fatigue accumulation and recovery time. Sgarbossa and Vijayakumar (2020) developed an optimisation model for the RA based on the RA equation developed by Calzavara et al. (2019a). The model accounted for the ageing factor of pickers, tasks, and rest combinations in the picking schedule, aiming to minimise the workers' fatigue level, reducing the total work, and accordingly increasing productivity. Al-Araidah et al. (2021) studied a manual order-picking system in a high-demand rate warehouse. The study investigated the energy expenditure rate of female pickers and their fatigue allowance, considering some affecting factors, such as walking speed, body weight, and throughput rate.

To the best of the authors' knowledge, no study accounted for MOP and HEE zone picking, which is the research gap that will be investigated in this research, as explained in detail in the introduction section. Therefore, this work expands the work by Al-Araidah et al. (2021) to account for additional warehouse and human factors and picking scenarios. The methodology and details of the model are presented in the next section.

2. Research methods

In this section, the proposed model will be described beside the description of store layout, routing and picking. Then, the calculations used in this research will be presented. At the end of this section, the methodology steps are summarised.

2.1. Model description

This study utilises Monte Carlo simulation to generate picking routes and computes associated HEE and throughput of the picking system. The model relies on multiple sources of data from the literature, including HEE equations, predetermined time standards (PTS), human statistics, and job standards. The model was coded using Excel spreadsheets.

For the purpose of this study, a traditional warehouse design with a predefined layout and pre-fixed dimensions was created. In this design, all storage cells were identified by their (x, y, z) coordinates, and hence, the distances between any two cells could be calculated. The assumed total number of available locations inside the warehouse zone is 1620 locations/cells, and each generated location is reserved for one item only. Statistics on body weights were obtained from the National Health Statistical Report (Fryar et al., 2018).

The Monte Carlo simulation method randomly generates coordinates of items' locations inside the warehouse for a given number of items per order. Utilising input data and the time and energy equations from the literature, the model computes the time and HEE for each movement of each randomly generated picking tour. Many orders (replicates) are simulated to obtain the required statistics on throughput and HEE. For the purpose of this study, the number of replicates is fixed at 2000 replicates. Computed statistics include the average and standard deviation of the travel distance, travel time, travel energy, picking time, and picking energy. Moreover, time results are accumulated to estimate the number of orders fulfilled per work shift. Furthermore, results are manipulated to test the impact of RA on throughput.

The below sections detail design components and equations utilised in the proposed model.

2.2. Warehouse design

Warehouse layout configuration and routing policy are essential and have a marked effect on order picking. It affects the duration of the picking tour and the time needed to achieve the tasks. Accordingly, it affects the workers' HEE and throughput. A typical warehouse design usually starts with identifying the required area, selecting the suitable racking method, determining the layout configuration, and finally, identifying the operating policies (Roodbergen et al., 2008). Fig. 1 shows the layout configuration of the warehouse used in this study. The warehouse consists of four zones, and each zone includes 15 double racks, as shown in Zone 1. The used layout is compact in space and assumes less travel (Caron et al., 2000). The compartments in each rack are given a number to facilitate the assignment of products to compart-

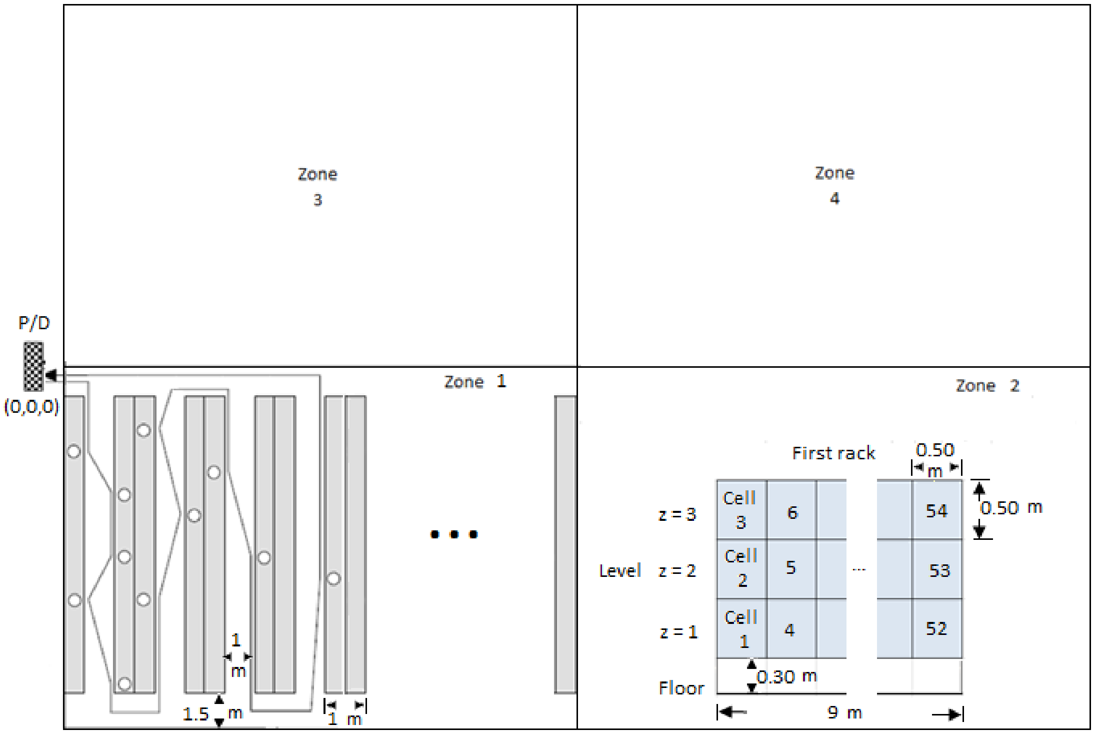


Fig. 1. Layout of the warehouse; zones, racks with a sample path of a picking tour and the numbering of cells/compartments in the first rack

ments. A sample numbering is shown in Zone 2 of Fig. 1 for the compartments of the first rack. Items are assumed to be located at the centre of the compartment and close to the opening of the compartment. Moreover, items are packaged to facilitate one-hand picking.

2.3. Routing and picking

All picking tours are assumed to start from and end at the pick-up/drop-off station (P/D), which is assigned a (0, 0, 0) coordinate. The picking tour starts when the order picker collects the order invoice from the P/D station. The invoice has n items assumed to be preordered to expedite picking. The picker travels to the items' locations based on the order in the invoice. To travel from the location of item i to that of i+1, the picker is assumed to walk in the middle of the aisle at a constant speed and to choose the shorter path to the target location. Moreover, the picker is assumed to use a shopping cart to move the picked items during the picking tour. The total travel distance/time is computed as the algebraic sum of the distances/times between visited locations, including that from and to the P/D station.

To collect an item from a compartment, the picker arrives at the position, rotates to face the rack, searches for the item, performs the pick, rotates back, stoops to place the item in the cart, and then continues to the next location. To perform a pick, the picker is assumed to position oneself at a convenient distance in front of the compartment. Based on the item's height, the picker is assumed to stand to pick items from upper and middle compartments (z=3 and z=2) or squat to pick items from lower compartments (z=1) to facilitate safe reach for the item. Following this, the picker reaches for, grasps, moves the item towards their body, reassumes the standing posture as needed, and then places the picked item in the cart. By the end of the tour, the picker empties the items from the cart at the P/D station. The time required to assume the needed posture (rotate, stand, stoop, or squat), the time to pick (reach for, grasp, move, and release) an item, and the time to lower the item into the cart are estimated using PTS systems, Tompkins et al. (2010) and Meyers and Stewart (2002). Times for eye travel and eye fixation are included for locating the item. It is worth mentioning that the item's weight may only impact the time required to move the item and that gender has no effect on the travel or the picking times. For convenience, these times are pre-estimated and are used as fixed inputs in the model, as shown in Table 1. The total picking time is computed as the algebraic sum of the time required to

Tab. 1. PTS picking time calculations

Activity	Description	Z = 1	Z = 2	Z = 3	Pick Invoice	Drop Items
Turn	To face the rack	0.020	0.020	0.020	0.02	0.02 once for all items
Eye Travel	Search for the item	0.010	0.010	0.010	0.01	0.01
Eye fixation	Locate the item	0.005	0.005	0.005	0.005	0.005
Squat (sit)	For safe picking from a lower shelf	0.020				
Reach 16 inches	Reach for the item	0.011	0.011	0.011	0.011	0.011
Grasp	Grasp a large item	0.003	0.003	0.003	0.009	0.003
Move 16 inches	Move the item toward the body or to the P/D station	0.011 + 25 % for every 10 lb over 5 lb				
Arise from squat (stand)	Stand tall	0.020				
Move 16 inches	To place the item in the cart	0.011 + 25 % for every 10 lb over 5 lb				
Release	Release the item into the cart or at the P/D station	0.000	0.000	0.000	0.000	0.000
Reach (16, 25.6, 45.3 inches for z= 1, 2, 3)	Reach back toward the body	0.011	0.0158	0.02565		
Turn	To align with the cart	0.020	0.020	0.020	0.02	0.02 once for all items
Total	Item weight ≤5 lb	0.142	0.1116	0.1313	0.076	0.04 + number of items × 0.03
	5< item weight ≤15 lb	0.1475	0.1183	0.140463		0.04 + number of items × 0.04275
	15< item weight ≤25 lb	0.153	0.125	0.149625		0.04 + number of items × 0.0455

collect the invoice at the beginning of the tour, the picking times of items, and the time required to empty the items at the P/D station. The total time of the picking tour is computed as the algebraic sum of

2.4. Energy calculations

To estimate the rate of energy expenditure during a picking tour, the tour is decomposed into travel and picking activities. This study predicts the rate of HEE for each activity using the following equations from Garg et al. (1978). Other than standing activities, all computed HEE must be adjusted by adding an HEE for standing during the activity to account for holding the body in position (Garg et al., 1978).

Walking on a flat surface (kcal/min):

$$E = 10^{-2}\,(51 + 2.54\,BW \times V^2) \tag{1}$$

Standing (kcal/min):

$$E = 0.024\,BW \tag{2}$$

Standing in a bent position (kcal/min):

$$E = 0.028\,BW \tag{3}$$

Arm lowering (kcal/lower):

$$\Delta E = 10^{-2}\,(0.093\,BW\,(h_2 - 0.81) + +(1.02\,L + 0.37\,S \times L)\,(h_2 - h_1)) \tag{4}$$

Forward movement of the arm while standing (kcal/movement):

$$\Delta E = 10^{-2}\,(3.75 + 1.23\,L)\,X \tag{5}$$

Forward movement of the arm while sitting (kcal/movement):

$$\Delta E = 10^{-2}\,(6.3 + 2.71\,L)\,X \tag{6}$$

Squat lowering (kcal/lower):

$$\Delta E = 10^{-2}\,(0.511\,BW\,(0.81 - h_1) + +0701\,L\,(h_2 - h_1)) \tag{7}$$

Squat lifting (kcal/lift):

$$\Delta E = 10^{-2}\,(0.514\,BW\,(0.81 - h_1) + (2.19\,L + +0.62\,S \times L)\,(h_2 - h_1)) \tag{8}$$

Stoop lowering (kcal/lower):

$$\Delta E = 10^{-2}\,(0.268\,BW\,(0.81\text{-}h_1) + +0.675\,L\,(h_2\text{-}h_1) + 5.22\,S\,(0.81\text{-}h_1)) \tag{9}$$

Stoop lifting
(kcal/lift):

$$\Delta E = 10^{-2}\,(0.325\,BW\,(0.81\text{-}h_1) + +(1.41\,L + 0.76\,S \times L)\,(h_2 - h_1)) \tag{10}$$

Where:
E: human energy expenditure per time (kcal/min)
ΔE: human energy expenditure per task (kcal)
BW: body weight of the worker (kg)
h_1: vertical height, in metres, from the floor; the starting (ending) point for the lift (lower)
h_2: vertical height, in metres, from the floor; the ending (starting) point for the lift (lower), $0.81<h_1<h_2$
L: item's weight (kg)
S: gender (0 female, 1 male)
V: walking speed of the worker (m/sec)
X: horizontal movement (m)

$$\Delta E = 2.4 \text{ x } 10^{-4} \times \mu \times G \times L_T \times D \tag{11}$$

Where:
μ: the coefficient of friction between the cart's wheels and the floor
L_T: the total weight of the load (kg), including the weight of the cart
D: distance (metres)
G: gravitational acceleration (9.8 m/sec^2)

To estimate the HEE during the pushing of the shopping cart to move the picked items, the model assumes that the handle of the cart is 1.2 metres in height and that the worker's arms make a 30o angle with the horizontal while pushing the cart. For the purpose of the study, the weight of the cart is assumed to be 35 kg (Dc Graves, 2023). The energy consumed to overcome the friction between the wheels of a cart and a floor can be computed as follows (Garg et al., 1978):
Pushing (kcal):

$$\Delta E = 2.4 \text{ x } 10^{-4} \times \mu \times G \times L_T \times D \tag{11}$$

Where:
μ: the coefficient of friction between the cart's wheels and the floor
L_T: the total weight of the load (kg), including the weight of the cart
D: distance (metres)
G: gravitational acceleration (9.8 m/sec^2)

The value of μ depends on the type of surfaces in contact. For the purpose of this study, the cart is assumed to have nylon or polyurethane mounted on steel wheels and the floor is assumed to be concrete; $\mu = 0.06$ (Al-Eisawi et al., 1999).

Compared to Zone 1 (Fig. 1), the difference in the HEE for the different zones can be estimated by the added HEE due to the travel between the P/D station and the first item while the cart is empty plus the HEE due to the travel between the last item and the P/D station while the cart is full. On the other hand, the HEE required to travel between items and to pick items is independent of the zone.

Equation 12 estimates the percentage of RA for pickers in the case that the rate of the HEE for the job exceeds the allowable HEE rate based on Price (1990). This study assumes that the allowable rate of the HEE is 4.3kcal/min for males and 2.6kcal/min for females (Price, 1990) and that the picker will spend their rest time standing.

Rest
Allowance:

$$\%RA = \frac{HEE_{work} - HEE_{allowable}}{HEE_{allowable} - HEE_{relaxation}} \times 100\ \% \tag{12}$$

Where:
$\%RA$: percentage of the required rest allowance
HEE_{work}: rate of energy consumption in a certain job (kcal/min)
$HEE_{allowable}$: allowable rate of energy consumption (kcal/min)
$HEE_{relaxation}$: rate of energy expenditure during rest time (kcal/min)

For high values of %RA, the inclusion of RA in the picking tour may significantly reduce the throughput of the picker because the total productive time of the picker will be reduced by an average of %RA. This is especially true for picking tours with high travel distances, pickers with high body weights, pickers walking at high speeds, and for combinations of previous factors. Specific findings of this study are presented in the next section.

2.5. Methodology steps

The next steps were followed by applying the methodology. First, items with their mass, location, and availabilities were stored in an Excel file. Second, datasets were randomly generated, containing the number of items per order and the locations of items based on stored data. Third, routings were generated as described in Section 3.3, and then, the time needed to complete the route was calculated as described in Table 1. Fourth, energy consumed by pickers was calculated as explained in Eq. 1–10. Fifth, this procedure was repeated many times (replicates = 2000); different measures were reported and evaluated, such as travel distance, travel time, travel energy, picking time, and picking energy.

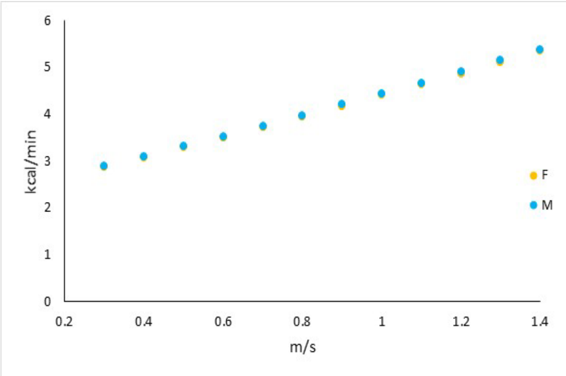
3. Research results

In this study, the Monte Carlo simulation was set to pick 2000 orders of the same number of items from different locations within Zone 1 (Fig. 1). Replicates of the simulation were executed to study the impacts of various warehouse, human, and trip factors on the rate of the HEE (kcal/min) and the throughput of the order picker (orders/shift). The work shift was assumed to be 480 minutes, excluding rest breaks. Allowable kcal/min were set at 2.6 and 4.3 for females and males, respectively. Input parameters are shown in Table 2. Note that body weights were selected to ensure that HEErelaxation was less than HEEallowable. The model was run for the two extremes to estimate the range of kcal/min and throughput for the assumed order-picking system. Extreme one (male picker, 120 kg body weight, 1.4 m/s, 10 kg items, and 10 items per tour) yielded an average HEE rate of about 7.48 kcal/min and a throughput of 141 orders per tour (1412 items). Extreme two (female picker, 45 kg body weight, 0.3 m/s, 0.5 kg item, and 1 item per tour) yielded an average HEE rate of about 1.89 kcal/min and a throughput of 187 orders per tour (187 items). The results showed significant differences in kcal/min and throughput. Moreover, the difference between the allowable kcal/min and the work kcal/min should be closely observed when assigning orders to workers.

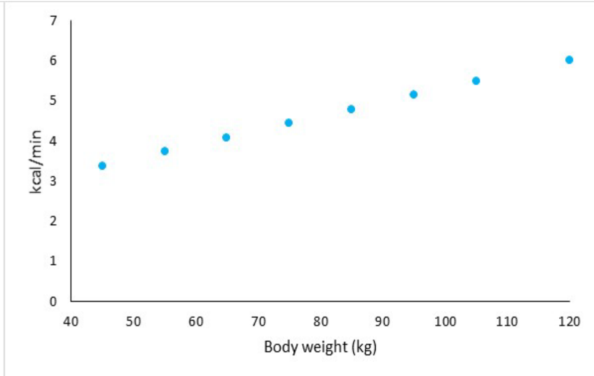
Tab. 2. Input parameters

Parameter name	Values / Range of values
Gender of a worker	1 for male, 0 for female
Worker’s body weight	45 to 105 kg for female 45 to 120 kg for male
Walking speed	0.3 to 1.4 m/sec
Weight of the item	0.5 to 10 kg
Number of items per order	1 to 10

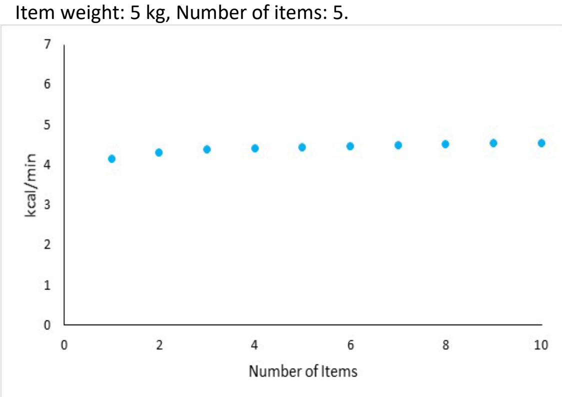
Fig. 2 shows the impact of each studied factor on the HEE rate and the throughput of the picker without RA. Fig. 2a shows the impact of the picker’s gender (F/M) and the walking speed (m/s) on the HEE rate (kcal/min). No significant effect of gender could be observed, <0.75 % and the significant impact of walking speed was highly recognisable. Therefore, the picker could significantly decrease their HEE rate by assuming a slower pace. Accordingly, warehouse management should keep their workers safe and not encourage rapidity. Since no significant impact of gender was observed, the rest of the experiments were performed assuming a male picker. Fig. 2b illustrates the significant impact of the picker’s body weight on the HEE rate. It is obvious that body weight is not totally controllable; even if management insisted on hiring workers with lower body weights, they could not guarantee that weight would not build up over time. The picker is expected to drain their energy early in the shift when combined with faster walking speed. Therefore, management may encourage workers with higher body weights to assume a slower pace to avoid negative consequences. Figs. 2c and 2d show the impact of the number of items and the item weight on the kcal/min. Combining these impacts with those of other factors may add up and make the total kcal/min far above the allowable. In the traced scenario in Fig. 2c, e.g., the average kcal/min for picking one item at a time is about 4.15, less than the allowable kcal/min, while it equals 4.53, greater than the allowable kcal/min, for picking ten items. Moreover, Fig. 2d shows that picking five items of 0.5 kg each consumes around 4.2 kcal/min compared to about 4.7 kcal/min when the item weight is 10 kg. Fig. 2e shows no significant change in the output when the simulation is repeated. In summary, Fig. 2 shows that body weight and walking speed have the most significant impacts on the HEE rate. The rate is further increased by increasing the number of items picked per tour and by the increase in the item weight.



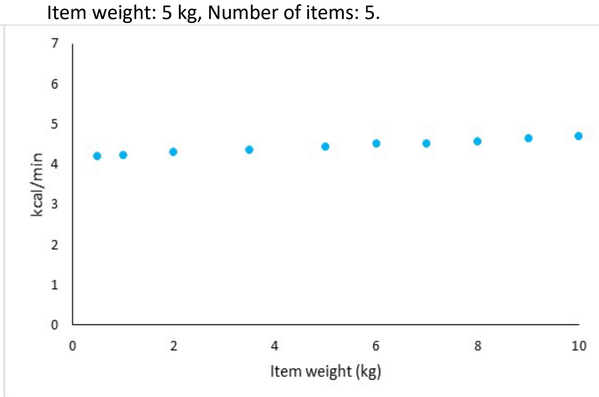
a) Effect of gender (M/F) and walking speed. Body weight: 75 kg, Item weight: 5 kg, Number of items: 5.



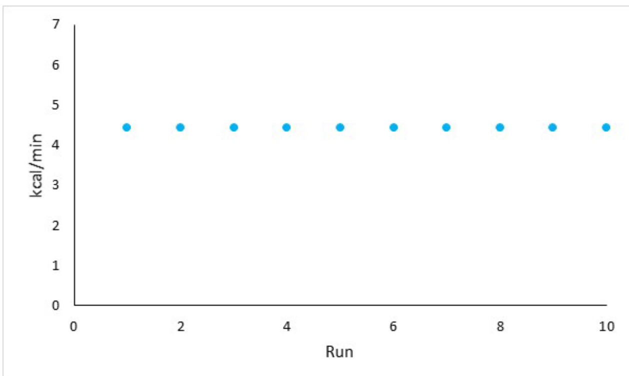
b) Effect of body weight. Gender: Male, Walking speed: 1.0 m/s, Item weight: 5 kg, Number of items: 5.



c) Effect of the number of items. Gender: Male, Body weight: 75 kg, Walking speed: 1.0 m/s, Item weight: 5 kg.



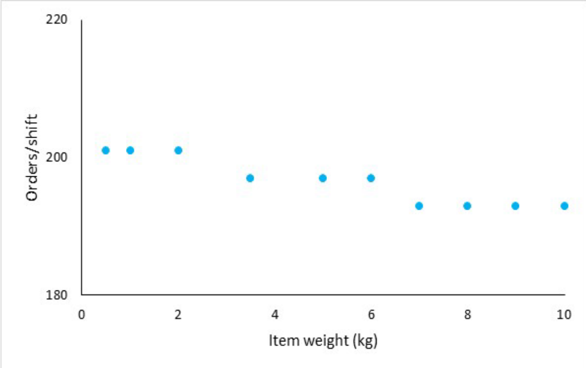
d) Effect of the item's weight. Gender: Male, Body weight: 75 kg, Walking speed: 1.0 m/s, Number of items: 5.

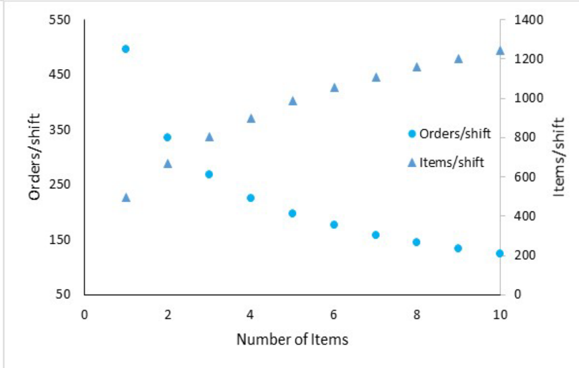


e) Effect of experiment replications. Gender: Male, Body weight: 75 kg, Walking speed: 1.0 m/s, Item weight: 5 kg, Number of items: 5.

Fig. 2. Effects of human and picking factors on the HEE (kcal/min) of order pickers with no rest allowance

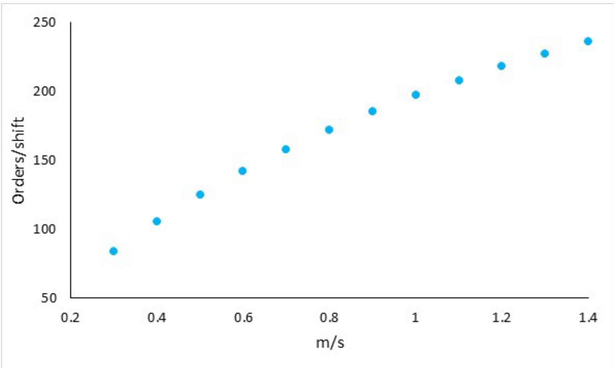
Fig. 3 shows the impact of the factors that contribute to increasing the tour time, which in turn impacts the system's throughput. Fig. 3a shows a slight decrease in the number of orders fulfilled per work shift. The slight drop, about four orders per weight group, in the number of orders is due to the increase in picking times: 25 % for every 10 lb above 5 lb of item weight, contributing to a few added seconds per pick. On the other hand, Fig. 3b shows a significant decrease in the number of orders fulfilled per work shift due to the added travel time. Although the number of orders decreases, the total number of items picked per tour increases as the order size increases. Therefore, management may consider the number of picked items instead of the number of orders fulfilled per work shift as a key performance indicator to balance work among pickers. Fig. 3c illustrates the significant impact of the walking speed of the picker on the number of orders fulfilled per work shift. Although faster pace means less travel





a) Effect of the item's weight. Gender: Male, Body weight: 75 kg, Walking speed: 1.0 m/s, Number of items: 5.

b) Effect of the number of items. Gender: Male, Body weight: 75 kg, Walking speed: 1.0 m/s, Item weight: 5 kg.



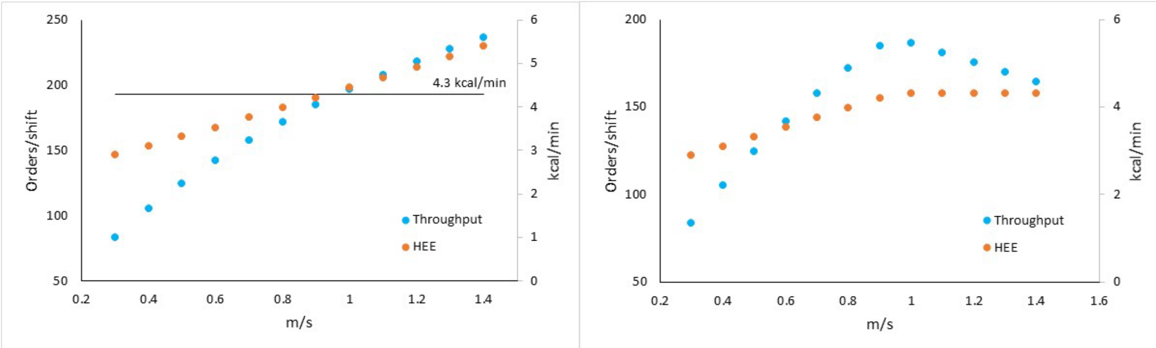
c) Effect of the walking speed. Gender: Male, Body weight: 75 kg, Item weight: 5 kg, Number of items: 5.

Fig. 3. Effects of human and picking factors on the throughput (orders/shift) of the order picking system with no rest allowance

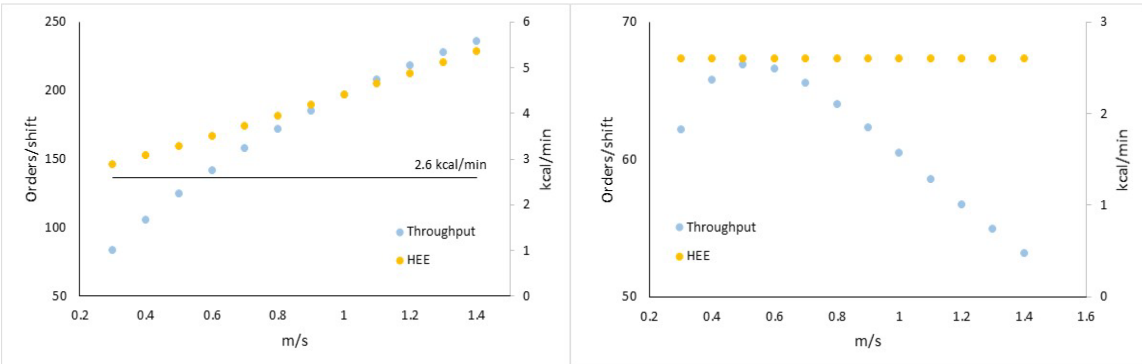
time and more output, it also means higher HEE rates, as seen in Fig. 2a. This calls for a balance between the two contradicting goals: to maximise throughput while keeping the HEE rate below the allowable.

Mini breaks, Eq. 12, can be introduced to reduce the kcal/min for a worker. This study assumed that the worker spends the break standing. Fig. 4 shows the impacts of introducing the mini-break on the kcal/min and the throughput of the picker for the given scenarios. Figs. 4a and 4b illustrate the impact for a male picker and Figs. 4c and 4d illustrate the impacts for a female picker. The figures provide the optimal walking speed for the picker that maximises their throughput while preserving energy. It can be clearly seen that walking speed is significantly lower for female pickers since they have lower allowable kcal/min. It is worth reminding that the allowable kcal/min for individuals may vary with age and health conditions. Therefore, management has to encourage workers not to force themselves beyond their capabilities to avoid injuries in the short and long term.

By layout symmetry (Fig. 1), the HEE rate and the throughput of the picker are similar for Zones 1 and 3 and are similar for Zones 2 and 4. Given the same sequence of items used before, a male picker of 75 kg body weight is walking at 1.0 m/s to pick five items each of 5 kg per the tour. The results obtained for picking from Zone 1 yielded an average travel distance of 85.23 metres, a HEE rate of about 4.43 kcal/min, and a throughput of 196.86 orders/shift. To estimate the effect of the zone on the HEE rate and the throughput of the picker, the model was executed for picking the locations; only the y-coordinate of the items was adjusted so that all items would be located in Zone 2. The obtained results yielded an average travel distance of 145.23 metres, a HEE rate of about 4.47kcal/min, and a throughput of 139.60 orders/



Gender: Male, Body weight: 75 kg, Allowable HEE: 4.3 kcal/min, Item weight: 5 kg, Number of items: 5. (left) with no rest, (right) with rest



Gender: Female, Body weight: 75 kg, Allowable HEE: 2.6 kcal/min, Item weight: 5 kg, Number of items: 5. (left) with no rest, (right) with rest

Fig. 4. Estimate of optimal average walking speed for a given combination of human and picking factors

shift. Although the travelled distance and the throughput were significantly different between the two zones, the kcal/min did not change significantly. This can be explained by the added time, a total of one minute, due to travel, which in turn prevented a significant increase in the average HEE rate.

Conclusions

In this work, the effects of five factors on the human energy expenditure (HEE) and, consequently, the throughput of the picker are investigated for male and female pickers by utilising the Monte Carlo simulation. These factors are the worker's gender, body weight, walking speed, item weight, and the number of items picked per tour.

The results show that with no allowable rest, the HEE rate can be independent of the picker's gender for selected scenarios of low-weight items. Moreover, increasing the speed of a picker will significantly increase the HEE for both male and female pickers. Fixing all other factors, the HEE rate increased approx. from 2.9 to 5.3 kcal/min for the speed of 0.25 to 1.4 m/s. The male picker's body weight significantly affects the HEE, while the number of items and the weight of items have an insignificant effect on the male picker's HEE. To test the robustness of the Monte Carlo simulation, the output of each run was recorded, and a consistency was obtained in the results. Similarly, for the throughput, it is found that increasing the item's weight will slightly decrease the number of orders that are executed during the shift for male pickers. Additionally, for male pickers, increasing the number of items per order will significantly decrease the number of orders per shift, and increasing the speed of pickers will significantly increase the number of orders per shift. To reduce the HEE and keep it below the allowable rate, mini-breaks are allowed, and pickers are assumed to spend them standing. As results show, a speed of around 1.0 m/s for a given scenario will keep the HEE below the allowable rate for male pickers. So, considering the speed greater than this value should be incorporated with rests, leading to less throughput. The allowable

HEE rate is notably less for female pickers than the males' rate. Thus, rest allowances should be considered at low picking speeds to avoid injuries. Consequently, the throughput of female pickers will be low compared with the throughput of male pickers for the given scenario. Female pickers might be assigned to pick up lighter items to avoid such low throughputs.

Implications of this research were theoretical, which is the lack of equations that can be used in the calculation step. For example, it was found that all research depended on an equation published in 1978 to calculate the cart pushing energy. The following limitations of this work can be indicated. First, the model is limited to the zone-picking type, which makes the results invalid for other types, such as discrete and batch picking. Second, mass ranges are used to cover most of the common items, but rare items can be out of this considered range. Third, some factors were not considered in this research, although they can be significant, i.e., the picker's age.

This work can be extended in the future by applying the same concept for different store layouts, considering picking items with different weights in the same tour and investigating other factors, such as the picker's age.

Literature

Al-Araidah, O., Okudan-Kremer, G., Gunay, E. E., & Chu, C.-Y. (2021). A Monte Carlo simulation to estimate fatigue allowance for female order pickers in high traffic manual picking systems. *International Journal of Production Research*, *59*, 4711-4722.

Al-Eisawi, K. W., Kerk, C. J., Congleton, J. J., Amendola, A. A., Jenkins, O. C., & Gaines, W. (1999). Factors affecting minimum push and pull forces of manual carts. *Applied Ergonomics*, *30*(3), 235-245.

Baležentis, T., & Streimikiene, D. (2017). Multi-criteria ranking of energy generation scenarios with Monte Carlo simulation. *Applied Energy*, *185*, 862-871.

Battini, D., Glock, C. H., Grosse, E. H., Persona, A., & Sgarbossa, F. (2016). Human energy expenditure in order picking storage assignment: A bi-objective method. *Computers & Industrial Engineering*, *94*, 147-157.

Çakıt, E. (2016). Estimation of energy expenditure based on divided manual material handling task: Waste collection example. C*elal Bayar University Journal of Science, 13*, 51-54.

Calzavara, M., Glock, C. H., Grosse, E. H., Persona, A., & Sgarbossa, F. (2016). Models for an ergonomic evaluation of order picking from different rack layouts. *IFAC-PapersOnLine*, *49*, 1715-1720.

Calzavara, M., Glock, C. H., Grosse, E. H., Persona, A., & Sgarbossa, F. (2017). Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse. *Computers & Industrial Engineering*, *111*, 527-536.

Calzavara, M., Glock, C. H., Grosse, E. H. & Sgarbossa, F. (2019a). An integrated storage assignment method for manual order picking warehouses considering cost, workload and posture. *International Journal of Production Research*, *57*, 2392-2408.

Calzavara, M., Persona, A., Sgarbossa, F., & Visentin, V. (2019b). A model for rest allowance estimation to improve tasks assignment to operators. *International Journal of Production Research*, *57,* 948-962.

Caron, F., Marchet, G., & Perego, A. (2000). Optimal layout in low-level picker-to-part systems. *International Journal of Production Research*, *38*, 101-117.

De Vries, J., De Koster, R., & Stam, D. (2016). Exploring the role of picker personality in predicting picking performance with pick by voice, pick to light and RF-terminal picking. *International Journal of Production Research*, *54,* 2260-2274.

Dc Graves Industrial Steel Cart Index. Retrieved from https://www.dcgraves.com/Welded-Industrial-Steel-Carts-s/1818.htm

Elbert, R., & Müller, J. P. (2017). Manoeuvres in manual person-to-parts order picking systems: Is there a significant influence on travel time and metabolic rates? *IFAC-PapersOnLine*, *50*, 6894-6899.

Finco, S., Battini, D., Delorme, X., Persona, A., & Sgarbossa, F. (2020). Workers' rest allowance and smoothing of the workload in assembly lines. *International Journal of Production Research*, *58*, 1255-1270.

Fryar, C. D., Kruszan-Moran, D., Gu, Q., & Ogden, C. L. (2018). Mean body weight, weight, waist circumference, and body mass index among adults: United States, 1999–2000 through 2015–2016.

Garg, A., Chaffin, D. B., & Herrin, G. D. (1978). Prediction of metabolic rates for manual materials handling jobs. *American Industrial Hygiene Association Journal*, *39*, 661-674.

Gibbs, B. B., Kowalsky, R. J., Perdomo, S. J., Grier, M., & Jakicic, J. (2017). Energy expenditure of deskwork when sitting, standing or alternating positions. *Occupational Medicine*, *67*, 121-127.

Grosse, E. H., Glock, C. H., Jaber, M. Y., & Neumann, W. P. (2015). Incorporating human factors in order picking planning models: framework and research opportunities. *International Journal of Production Research*, *53*(3), 695-717.

Harrison, R. L. (2010). Introduction to Monte Carlo simulation. AIP conference proceedings. *American Institute of Physics*, 17-21.

Ho, Y.-C., & Liu, C.-F. (2005). A design methodology for converting a regular warehouse into a zone-picking warehouse. *Journal of the Chinese Institute of Industrial Engineers*, *22,* 332-345.

Horiuchi, M., Muraki, S., Horiuchi, Y., Inada, N., & Abe, D. (2014). Energy cost of pushing a wheelchair on various gradients in young men. *International Journal of Industrial Ergonomics*, *44*, 442-447.

Liftingsafety (2023). Retrieved from https://www.liftingsafety.co.uk/product/order-picking-trolley-1112.html

Marmidis, G., Lazarou, S., & Pyrgioti, E. (2008). Optimal placement of wind turbines in a wind park using Monte Carlo simulation. *Renewable Energy*, *33*, 1455-1460.

Meyers, F. E., & Stewart, J. R. (2002). *Motion and time study for lean manufacturing*. Pearson College Division.

Ocobock, C. (2016). Human energy expenditure, allocation, and interactions in natural temperate, hot, and cold environments. *American Journal of Physical Anthropology*, *161*(4), 667-675.

Papadopoulos, C. E., & Yeung, H. (2001). Uncertainty estimation and Monte Carlo simulation method. *Flow Measurement and Instrumentation*, *12*, 291-298.

Parikh, P. J., & Meller, R. D. (2008). Selecting between batch and zone order picking strategies in a distribution center. *Transportation Research Part E: Logistics and Transportation Review*, *44*, 696-719.

Petersen, C. G. (1997). An evaluation of order picking routeing policies. I*nternational Journal of Operations & Production Management*.

Petersen, C. G. (2002). Considerations in order picking zone configuration. *International Journal of Operations & Production Management.*

Petersen, C. G. & Aase, G. (2004). A comparison of picking, storage, and routing policies in manual order picking. *International Journal of Production Economics*, *92*, 11-19.

Petersen, C. G., Siu, C., & Heiser, D. R. (2005). Improving order picking performance utilizing slotting and golden zone storage. *International Journal of Operations & Production Management, 25*(10), 997-1012.

Pontzer, H., Durazo-Arvizu, R., Dugas, L. R., Plange-Rhule, J., Bovet, P., Forrester, T. E., ... & Luke, A. (2016). Constrained total energy expenditure and metabolic adaptation to physical activity in adult humans. *Current Biology*, *26*(3), 410-417.

Poulianiti, K. P., Havenith, G., & Flouris, A. D. (2018). Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries. *Industrial Health*.

Price, A. (1990). Calculating relaxation allowances for construction operatives—Part 1: Metabolic cost. *Applied Ergonomics*, *21*, 311-317.

Raychaudhuri, S. (2008). Introduction to monte carlo simulation. Winter simulation conference. *IEEE*, 91-100.

Roodbergen, K. J., Sharp, G. P., & Vis, I. F. (2008). Designing the layout structure of manual order picking areas in warehouses. *IIE Transactions*, *40*, 1032-1045.

Saderova, J., Poplawski, L., Balog Jr, M., Michalkova, S., & Cvoliga, M. (2020). Layout design options for warehouse management. *Polish Journal of Management Studies*, *22*(2), 443-455.

Sgarbossa, F., & Vijayakumar, V. (2020). *Reducing fatigue level through tasks and breaks assignment in order picking system*. 21st IFAC World Congress (Virtual) Berlin, Germany, July 12-17, 2020.

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). *Facilities planning*. John Wiley & Sons.

Vanheusden, S., Van Gils, T., Caris, A., Ramaekers, K., & Braekers, K. 2020. Operational workload balancing in manual order picking. *Computers & Industrial Engineering*, *141*, 106269.

Weisner, K., & Deuse, J. (2014). Assessment methodology to design an ergonomic and sustainable order picking system using motion capturing systems. *Procedia CIRP*, *17*, 422-427.

Westerterp, K. R. (2017). Control of energy expenditure in humans. *European Journal of Clinical Nutrition*, *71*(3), 340-344.