Ergonomics and Storage Base Position for U-shaped Picking Zones

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ABSTRACT

Manual picker-to-parts order picking systems are predominant in brick-and-mortar retail logistics. While flow-oriented approaches in operations management focus on performance and quality as primary outcomes, recent research aspires to integrate layout design and storage assignment with the ergonomic strains of workers.

In this work, we apply mathematical models that allow layout design and storage assignment optimization by taking pickers' energy expenditure into consideration. The objective is to find the position of the storage base that guarantees the lowest possible energy expenditure for the human pickers. This is achieved through a proper storage assignment based on the picking frequencies of the products. The innovation we introduce with respect to the previous research, is to allow the storage base to be placed out-centered with respect to the U-shaped corridor. Computational experiments are carried out on random and real-world datasets. The results indicate that positioning the storage base on one side, leading to asymmetric configurations, can clearly lead to superior ergonomic settings.

CCS CONCEPTS

• **Applied computing → Decision analysis**.

KEYWORDS

warehouse management, U-shaped corridors, layout design, storage base position optimization, storage assignment

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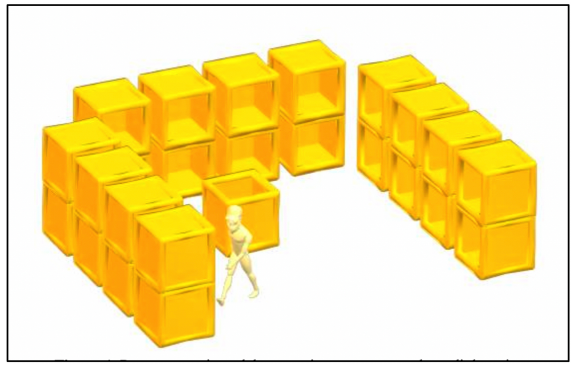

Figure 1: Example of a corridor with PCs.

1 INTRODUCTION

Order picking accounts for 50% to 75% of the total warehouse operating costs [6]. Although the use of automated systems has been gradually increasing, most of order picking operations are still carried out by human pickers due to higher flexibility [7]. Reasonable operating arrangements increase work efficiency and employees satisfaction levels in multiple aspects, and thereby reduce costs. Therefore, the analysis of order picking operations has always been of interest, aiming at a more efficient operational organization.

In recent years there has been an increasing focus on employee fatigue in the workplace [11], [19]. Scientific research shows that Muscolo-skeletal Disorders (MSD) has a significant impact on operating costs [3], [23] and the impact is expected to gain additional significance in the future, due to an ageing workforce [1]. In this study we are interested in optimizing the warehouse layout while considering physical effort aspects, aiming to reduce fatigue for employees and the overall probability of potential injuries.

In a typical warehouse there are corridors where pallet boxes, containing products, that are stacked on top of each other, see Figure 1 for an example. We will refer to the boxes as Pallet Cages (PC) in the rest of this article. From the perspective of the present study, the layout of a warehouse is defined by the proportion of the corridors, i.e., the ratio between the length of the horizontal and vertical sides. In each corridor, there is a storage base used to organize the products for specific orders, once collected from the PCs of the corridor. The pickers move back and forth between the PCs and the storage base.

The operations performed by a human picker while working can be separated in walking, picking, transport the products, and sorting them on the base. All these operations will be considered for an optimization of the layout of a corridor. In details, a good layout should be able to reduce the total metabolic costs by reducing the physical effort of the picker. Given the picking frequencies of the articles contained in the PCs – these can be obtained by historical data or marketing predictions – the aim of this study is to find an appropriate storage assignment policy for the different PCs, together with an ergonomic-optimized positioning of the storage base.

A model to solve the optimization problem concerning layout design and storage assignment of the U-shaped storage area by minimizing the total physical effort has been recently proposed in Diefenbach and Glock [8]. In their study they were considering positions for the storage base along the center of the corridor, with respect to the horizontal leg of the U-shape. In our study, we build on their ideas and propose an extension where the storage base does not have to be necessarily along the center of the corridor, but can be moved on the side, creating some asymmetry in the corridor. Note that the original study had strangely neglected this option. We will show that such a configuration can lead to better optimized solution in terms of expected total ergonomic effort, once reliable information about picking frequencies is available.

The remainder of this paper is structured as follows: in Section 2 we present a literature review on layout design, storage assignment and ergonomics in warehouse operations. In Section 3 we describe the model we have adopted for the estimation of pickers physical effort. Section 4 formalizes the U-shaped layout considered in the study, while Section 5 describes the optimization procedure. Experiments with both random and real-world instances are described in Section 6. Conclusions of the study are summarized in Section 7.

2 LITERATURE REVIEW

Design and operations of warehouses in the context of order picking has been extensively studied in the literature. Topics covered include layout design, storage assignment, zoning, batching and routing. General analysis on zoning, batching and routing problems can be found in [7], [17], [30].

The layout design problem can be aggregated at various levels. The perspective ranges from location planning [20], department arrangement inside the warehouses [18], to determining the number, orientation, and the arrangement of the shelves etc. The latter problems are highly interdependent with order picking problems, particularly in the field of storage assignment, zoning and routing. Although automated warehouses are getting more and more popular, manual systems still account for a large proportion in the current situation. For the latter systems, in [28] the average travel distance of a picker is analyzed with different routings on different layout arrangements. The heights of the shelves and storage pallets are evaluated from an economic and ergonomic point of view in [5].

In recent years the physical effort has been integrated into decision support models for order picking activities. It is tied to the fact that common movements in manual order picking systems such as lifting, lowering and carrying objects have repeatedly been shown as a major risk factor for developing MSDs [22], [27], [29], that in turns lead to important negative economic impacts, as mentioned early.

Traditional layouts for warehouses consist of multiple zones with shelves organized in U-shape is considered in [12]. Studies on improving the performance of the U-shaped layout are carried out about pickers learning [16] and the use of semi-empty pallets that allow easier object extraction [13].

Optimization has been widely applied in the logistic sector [9], [24], [25], [31], [32]. In terms of storage assignment problems, studies on different storage policies can be find for random storage, class-based storage and dedicated storage [7], [17]. The most common topics are about the minimization of the total travel and picking time, regarding the characteristics of the shelves [26]. Physical effort has been considered in [2], [10], [19], [21]. In [8], which is the starting point of the present study, it is shown that optimizing storage assignment and layout design in terms of economic or ergonomic strain is in fact equivalent, since a solution inefficient according to physical indicators almost directly translates into a solution with a longer operational time.

3 CALCULATION OF PICKERS' ERGONOMIC STRAINS

As pointed out in [8], the operations repeatedly performed by a human order picker inside the corridor, can be classified as follows:

(1) Walking from the storage base to a PC. The effort consists in walking from the base to the position in which the PC is located.
(2) Picking the product from a PC. The effort is determined by the specific location of the product: the picker needs to bend over if the product is placed at the bottom positions or raise arms if the product is placed on the top positions. The effort also consists of taking the product out of the PC.
(3) Transporting the product to the storage base. The effort is determined by carrying the product and walking at the same time.
(4) Putting the product on the storage base. The effort is the operation of bending down with the product and drop it on the base.

To obtain the estimations required for the physical effort study, we consider the average target individual as a male, 1.78m in height and 75kg in weight. The distance from his hands to the ground h_a is equal to $\frac{3}{7}$ of his total height (0.76 m). The PCs are cubes of size l_{pc} = 1m, and the safety distance between two PCs l_s is 0.2m. Therefore, if we consider each position as a storage unit, the length and width can be represented as 1.2m. PCs are disposed in stacks of 2 PCs. In out model, the picker picks the products from the middle height of the PC. Therefore, the picking height for PC in bottom position h_b is 0.5m, and the picking height for PC in top position h_t is 1.5m. We assume there is no obstacle on the ground and that the picker can walk over the entire surface of the corridor without constraints (S=100%). The average walking speed considered v is 1.4m/s. We define BW as the body weight of the picker, we_i as the weight of the product i. The formulae from [10], used to calculate the energy expended for each kind of task are adapted as follows. Energy spent on walking without load (kcal/m):

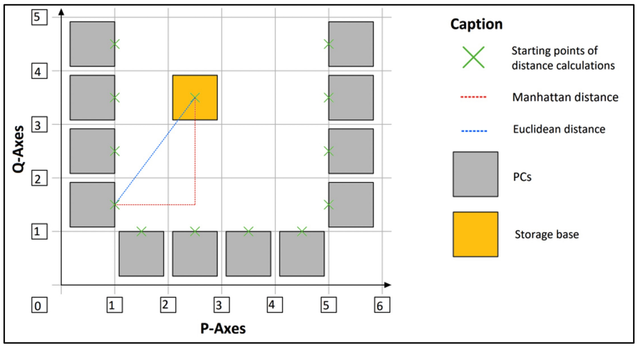

Figure 2: Example of two-dimensional representation of a corridor.

$w^w = \frac{51+2.54\cdot BW\cdot v^2+0.379\cdot BW\cdot S\cdot v}{6000} = 0.0773625$

Energy spent on walking with load (kcal/m):

$w_i^c(we_i) = \frac{80+2.43\cdot BW\cdot v^2+4.63\cdot we_i\cdot v^2+4.99\cdot we_i+0.379\cdot BW\cdot S\cdot v}{6000} =$

$= \frac{79.501+2.371\cdot we_i}{10^3}$

Energy spent to take product from bottom position (kcal/task):

$w_i^b(we_i) =$

$= \frac{0.268\cdot BW\cdot(0.81-h_b)+0.675\cdot we_i\cdot(h_a-h_b)+4.228-5.22h_b}{3000} =$

$= \frac{261.64+5.85\cdot we_i}{10^5}$

Energy spent to take product from top position (kcal/task):

$w_i^t(we_i) = \frac{0.062\cdot BW\cdot(h_t-0.81)+2.67\cdot we_i\cdot(h_t-h_a)]}{3000} = \frac{10.695+6.586\cdot we_i}{10^4}$

Energy spent to sort the product in the storage base (kcal/task):

$w_i^d(we_i) =$

$= \frac{0.325\cdot BW\cdot(0.81-h_b)+0.65\cdot we_i\cdot(h_a-h_b)}{3000} = \frac{251.87+5.63\cdot we_i}{10^5}$

These values will be used to estimate the physical effort of workers while executing picking operations. These estimates will in turn be used to guide the layout design and storage assignment optimization, as described in Section 5.

4 MODEL OF THE PICKING AREA

In this study – and consistently with [8] – we consider U-shaped picking areas, that can be formally described as follows. We first represent a single corridor inside the warehouse within a Cartesian plane. Figure 2 shows a two-dimensional representation of a corridor with PCs. We use a set I for the PCs, a set P for the discrete horizontal coordinates and a set Q for the vertical coordinates. The pairs of values (p, q) with $p = \{1, |P|\}$, $q \in \{2, |Q|\}$ or $q = 1$, $p \in \{2, |P| - 1\}$, are identified by grey blocks in the figure and represent locations where PCs are stored. Note that although only one layer of PCs is considered in this simplified description above, a more realistic multi-level configuration will normally be used. In our case we will consider a configuration with two layers: a bottom position corresponding to PCs on the ground, and a top position, with PCs stacked on top of PCs on the ground. The starting point of the picker is approximated as the center of the storage base, the picking point is the midpoint of the side of the PC facing the picker.

While a pair (p, q) describes the location of the storage unit within the corridor, the actual distances are calculated by considering that each square in the figure is 1.2m long. The square edge is given by l_{pc} = 1m (size of a PC) plus l_s = 0.2m (safety distance between two adjacent PCs). The distance between the storage base and a PC used in this work is calculated by weighing the Euclidean distance and the Manhattan distance as already proposed in [14]. This should approximate well the walking pattern of workers. With (b_p, b_q) being the position of the base and (p, q) being the location of a PC, the walking distance d_{pq} considered is calculated as follows:

$$d_{pq} = \frac{\overbrace{\sqrt{(b_p-p)^2+(b_q-q)^2}\cdot 1.2}^{\text{Eucledian distance}} + \overbrace{\left(|b_p-p|+|b_q-q|\right)\cdot 1.2}^{\text{Manhattan distance}}}{2}$$

5 OPTIMIZATION

In this section we discuss three incremental optimization steps. First we assume the layout of the corridor and the storage base location are known, and we solve the storage allocation problem, with the aim of positioning articles into the shelves based on their picking frequency and weight, in such a way to minimize the effort of the picker. In the second step, given a layout, the picking frequencies and weights of the articles, we find the optimal position of the storage base. In the third step we also optimize the layout given the number of articles to store and their characteristics.

5.1 Storage Allocation Optimization

In this section we summarize the optimization method originally proposed in [8]. Given a position of the storage base and the shape of the corridor, the optimization model adopted optimized storage allocation (the position of the PCs) based on the picking frequencies of products, with f_i being the picking frequency for the products in PC i. Intuitively, we will want to place the most popular articles as close as possible to the base, aiming to minimize the effort required to pick them. The storage base position is given as (b_p, b_q). The distances d_{pq} are calculated as described in Section 4, while the energy consumptions for the different tasks are estimated according to the rules defined in Section 3. A decision variable x^b_{pqi} takes value 1 if the PC i is assigned to the bottom position at location (p, q), 0 otherwise. Another decision variable x^t_{pqi} takes value 1 if the PC i is assigned to the top position at location (p, q), 0 otherwise.

The storage allocation model, assuming all the number of PC to allocate equals the number of available slots, can therefore be defined through the following Integer Linear Programming model:

$$\min \sum_{p\in P}\sum_{q\in Q}\sum_{i\in I} f_i \left(\begin{array}{c} d_{pq}\left((w^w + w_i^c)(x^b_{pqi} + x^t_{pqi})\right) + \\ +w_i^b x^b_{pqi} + w_i^t x^t_{pqi} + w_i^d \end{array} \right) \quad (1)$$

$$s.t. \sum_{p\in P}\sum_{q\in Q}(x^b_{pqi} + x^t_{pqi}) = 1 \quad i \in I \quad (2)$$

$$\sum_{i\in I} x^b_{pqi} = 1 \quad p \in P, q \in Q \quad (3)$$

$$\sum_{i\in I} x^t_{pqi} = 1 \quad p \in P, q \in Q \quad (4)$$

$$x^b_{pqi}, x^t_{pqi} \in \{0, 1\} \quad p \in P, q \in Q, i \in I \quad (5)$$

The objective function (1) aims at minimizing the physical effort. The first part calculates the energy spent by the picker to move from the storage base to PC and return to the base after taking a product. The second part considers the energy spent for picking the product from the PC depending on the position in which it is located (bottom or top). The third part considers the energy spent to sort the product on the storage base. The whole effort is multiplied by the picking frequency of the product. Constraints (2) guarantee that each PC is placed in a single position (p, q) and it could be only either at the top position or in the bottom position. Constraints (3) and (4) ensure that there is exactly one PC allocated to each slot (top and bottom positions). Note that since in this study all the available positions are considered as used, equations can be used instead of inequalities. This is realistic since dummy PCs with frequency 0 can be created to fill up the available slots. Finally, constraint (5) defines the domain of the variables. Note that the basic model discussed above can be easily rewritten as a Linear Sum Assignment Problem [4] (see [8] for details). The benefit is that the latter can be solved in polynomial time and thus provides a fast tool for applications and experiments.

5.2 Optimization of the Storage Base Location

In a situation where an existing picking area needs to be reorganized, together with storage assignment, it can also be strategic to reposition the storage base according to the new locations and picking frequencies of products.

Note that this is the area where we provide a methodological improvement with respect to the previous literature.

In the study presented in [8], the base position can take any feasible position such that on the Q axis, but it is constrained to be in the center of the P axis, therefore with $b_p = \frac{|P|}{2}$. A central position along the P axis for the storage area can be motivated by symmetry and flexibility in case of frequent changes of the products in the corridor, but it is rarely the optimal choice for a layout, since having the storage base on one side allows to maximize the high-frequency picking products in the proximity of the base. Therefore, in this work we add a further degree of freedom in the movement of the position of the storage base along the Q axis. We adopted a precision of 0.6m (half a storage unit), that is considered enough for a real application.

The optimization procedure used is based on the solution of multiple storage assignment instances, one for each potential location for the storage base. The location associated with the storage assignment with the lowest cost is the best one.

More formally, the optimization procedure for the storage base location is summarized in Algorithm 1, *OptBaseLocation*. The routine takes in input the values $|P|$ and $|Q|$ defining the layout of the corridor. After some initialization in lines 1 and 2, all possible feasible positions for the storage base are considered (line 3, note that half-integer values are allowed for the coordinates here) and for each of them the cost of an optimal storage assignment is calculated (line 4) in polynomial time by solving a Linear Sum Assignment Problem, as mentioned in Section 5.1. If the cost of the storage assignment is lower than the cost of the best solution retrieved so far (*CostBestLoc*) then the best solution and its costs are updated (lines 5 to 7). The coordinates of the best storage base location together with the corresponding storage assignment cost are returned in line 10.

Algorithm 1 OptBaseLocation($|P|$, $|Q|$)

1: BestLoc = (1,1)
2: CostBestLoc = $+\infty$
3: **for** each feasible pair (p, q) **do**
4:     Cost = cost of an optimal Storage Assignment with $b_p = p$ and $b_q = q$
5:     **if** Cost < CostBestLoc **then**
6:         BestLoc = (p, q)
7:         CostBestLoc = Cost
8:     **end if**
9: **end for**
10: **return** BestLoc, CostBestLoc

Note that the computational complexity of Algorithm 1 is polynomial as soon as a polynomial routine is used to solve (multiple times) the Linear Sum Assignment Problem at line 5. This is important because it keeps the running time acceptable even for large corridors.

5.3 Overall optimization of the Layout

This section covers the more general optimization faced when a new warehouse is designed, and there is the freedom to choose the shape of a corridor, given the number of PCs that need to be stored in it. Therefore, the optimization will consider all the possible pairs $(|P|, |Q|)$ that generate a feasible corridor containing exactly the desired number of PCs, and for each pair the algorithm *OptBaseLocation* will be launched. The overall layout, which means the shape of the corridor and the location of the storage base, with the lowest ergonomic strain will therefore be returned as the optimal one.

Given the desired storage capacity n of the area under design, all the feasible pairs of values for $|P|$ and $|Q|$ are considered. The minimum value that $|P|$ and $|Q|$ can take in the settings we consider is 5 (below these values there would be not enough distance between the storage base and the PCs and the corridor would be impractical).

The formal details of the approach are provided in Algorithm 2, *OptOverallLayout*. The routine takes in input the number of PCs n for which a corridor needs to be engineered. Initializations are carried out in lines 1 and 2, then all possible feasible pairs of $|P|$ and $|Q|$ with a given n are considered (line 3) and for each of them the routine *OptBaseLocation* is invoked (line 4). If the cost of the optimal storage base problem for the given values of $|P|$ and $|Q|$ improves the best overall layout cost retrieved so far (line 5) then the currently best layout, the relative storage base position and the relative cost are updated (lines 6 to 8). The composite information about the optimal solution is returned in line 11.

Note that the computational complexity of Algorithm 2 is polynomial as soon as a polynomial routine is used to solve (multiple times) the Linear Sum Assignment Problem inside the routine *OptBaseLocation*. Therefore, also designing from scratch the overall layout of a corridor can be done in tractable time.

6 COMPUTATIONAL EXPERIMENTS

In this section we will describe the datasets used in the study and present some computational experiments aiming at understanding

Algorithm 2 OptOverallLayout(n)

```
BestLayout = BestBaseLoc = (0,0)
CostBestLayout = +∞
for each feasible pair (|P|, |Q|) do
    BaseLoc, Cost = OptBaseLocation(|P|, |Q|)
    if Cost < CostBestLayout then
        BestLayout = (|P|, |Q|)
        BestBaseLoc = BaseLoc
        CostBestLayout = Cost
    end if
end for
return BestLayout, BestBaseLoc, CostBestLoc
```

the role of the storage base location in an optimized corridor design, under different conditions.

6.1 Test Instances

Three different datasets of products with the relative picking frequencies have been considered in this study. For each instance we will analyze different corridor sizes, with the aim of studying the best storage base location.

Note that the weight of the goods is reported although, according to the literature [8], this information is marginal when considering storage allocation. Therefore, our simulation study is focussed on the picking frequencies only.

6.1.1 Instances from [8]. From the instances adopted in [8] we selected 20 instances with 30 PCs, 20 instances with 60 PCs and 10 instances with 100 PCs for our experiments. In these instances the weights of the products were generated according to two uniform distributions, either between 5 and 25kg or between 12 and 18kg depending on the instance. The picking frequency varies from 8 picks/hour to 12 picks/hour. In all the instances the products have uniform picking frequencies within a small range.

6.1.2 Random Instances. The instances of this dataset have been generated at random, and they are available upon request to the authors. There are 40 instances with 30 PCs, 20 instances with 60 PCs and 12 instances with 100 PCs for each picking frequency distribution considered. The weights are sampled between 5 and 25kg according to a uniform distribution, while the picking frequencies are chosen according to different probability distributions, aiming to simulate different real scenarios. In details, picking frequencies are generated according to:

- an exponential distribution with λ=0.102, which implies an average picking frequency of $1/\lambda$=9.8 picks/hour. These instances simulate the scenario where there are a few products with high picking frequency, while most of the products have low picking frequencies. We will refer to these instances as random-exponential;
- a normal distribution with an average of μ=9.8 picks/hour and a standard deviation of σ=3.66 picks/hour. These instances simulate the scenario where most of the products have similar picking frequency around the average value, but there are also products with low picking frequencies. We will refer to these instances as random-normal;
- a uniform distribution between 1 and 18 picks/hour. These instances simulate the scenario where a random storage assignment policy is applied (see Section 2): the picking frequencies of the products in the corridor are evenly distributed in a wide range of possible values. We will refer to these instances as random-uniform.

6.1.3 Real Instances. The instances from this dataset are derived from real picking operations digitalized over time by a German grocery retailer. The picking data contains several characteristics of the articles and cover a timespan of 5 days. After having cleaned inconsistent data, we ended up with 28 instances with 30 PCs, 14 instances with 60 PCs and 8 instances with 100 PCs, corresponding to different corridors. The weight of the articles picked varies between 2 and 25kg. The minimum picking frequency recorded is 0.2 picks/hour, while the maximum is 10.7 picks/hour. The frequency distribution can be fitted as an exponential distribution with λ=0.573. From these instances we hope to understand if the simulation results remain valid in real-world settings, especially in presence of articles with very low picking frequencies.

6.2 Computational Results

All the experiments were carried out on computer with 2.6 GHz Intel Core i5-3230M processor and 16Gb of RAM. The optimization routines described in Section 5 were implemented in Python and the Linear Sum Assignment Problem mentioned in Section 5.1 was attacked with the dedicated solver available in Google OR-Tools[1], that implements the cost-scaling push-relabel algorithm originally described in Goldberg and Kennedy [15].

6.2.1 Optimal position of the Storage Base. In this section we assume the size of the corridor is given, as it normally occurs during a reorganization of a warehouse, and we consider a reference corridor shape, by setting $|P|$=10 and $|Q|$=12. It contains 60PCs and has size 12.0m×14.4m. We want to understand the optimal position of the storage base for the different datasets described in Section 6.1, taking in mind that – given the corridor configuration considered – the center of the storage base needs to be at least 3m away from each perimetral wall (1.2m of a PC plus 1.8m of manuvering distance), while a storage base at the center of the corridor along the P axis would correspond to a value of 6m.

Given a corridor and picking frequencies, the routine *OptBase-Location* (Algorithm 1) is run. It solves an instance of the model described in Section 5.1 for each possible feasible location of the storage base, so that to find the relative optimal storage assignment. The location of the storage base corresponding to the lowest optimal cost is classified as the optimal location.

The results show that the optimal position of the storage base is often towards one side of the axis P. An example of the results of a fixed layout that has a capacity of 60 PCs with $|P|$=10, $|Q|$=12 is shown in Table 1. We calculate the average value for the optimal base position for each dataset.

From the result in Table 1 we can observe that the optimal storage base position tends to be close to the products stored on the P axis. The intuition behind this is that having the base in that location allows to have a higher number of PCs directly near to it. This is not

[1] https://developers.google.com/optimization/assignment/linear_assignment

Table 1: Average optimal storage base position for a corridor with $|P|$=10 and $|Q|$=12 (60PCs).

Dataset		Average position	
Source	Distribution	P axis (m)	Q axis (m)
[8]	Uniform (small)	5.00	4.32
Random	Exponential	3.00	3.00
Random	Normal	5.00	3.00
Random	Uniform (large)	4.32	3.00
Real	Exponential	3.00	3.00

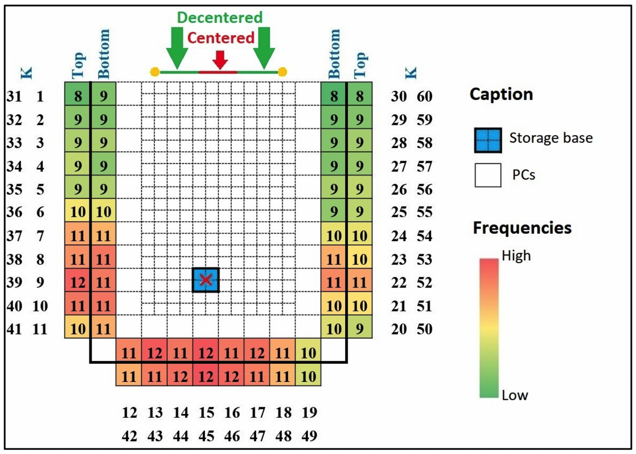

Figure 3: Storage assignment and position of the storage base for an instance from [8] (*uniform* distribution) with $|P|$ = 10 and $|Q|$ = 12. The numbers on the PCs are approximated picking frequencies.

true only for the instances from [8], for which picking frequencies follow a uniform distribution with a small range of values, with all products that tend to be equally important. For the same reason, the average position of the storage base is closer to the center of P axis in the instances with a uniform distribution of the picking frequencies. Such a case can be appreciated in Figure 3. In the remaining cases, the storage base tends to be positioned as close as possible to a corner of the corridor, where intuitively the high-picking articles are stored.

Figure 4 shows an example of a random picking area (corridor) with $|P|$ = 10, $|Q|$ = 12 and frequencies taken from the real instances (exponential distribution). As in this case there are only few products with high picking frequencies, while most of the products have low picking frequency, the optimal location for the storage base is located near the products that are more frequently picked. It is convenient to stay as low as possible on the Q axis, so that to be closer to the most popular products. Note that an equivalent optimal solution could be obtained by mirroring the storage assignment and storage base position over the Q axis.

Figure 5 shows an example of a corridor with $|P|$ = 10, $|Q|$ = 12 and random picking frequencies generated according to a normal distribution, from Dataset 2-normal. In this case there are more products with high picking frequencies than in the case depicted in Figure 4. Consequently, the average optimal location for the storage

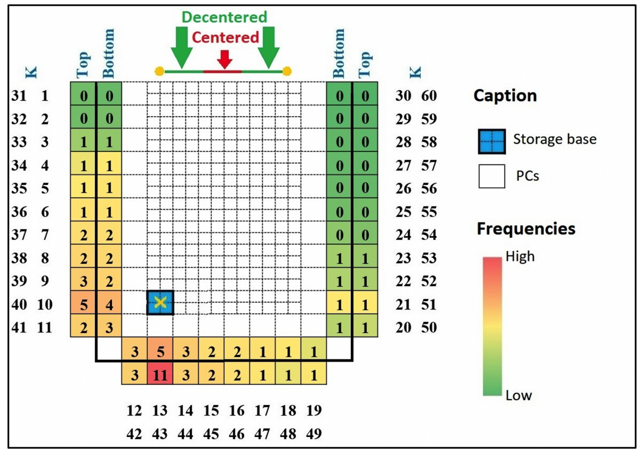

Figure 4: Storage assignment and position of the storage base for a real instance (*exponential* distribution) with $|P|$ = 10 and $|Q|$ = 12. The numbers on the PCs are approximated picking frequencies.

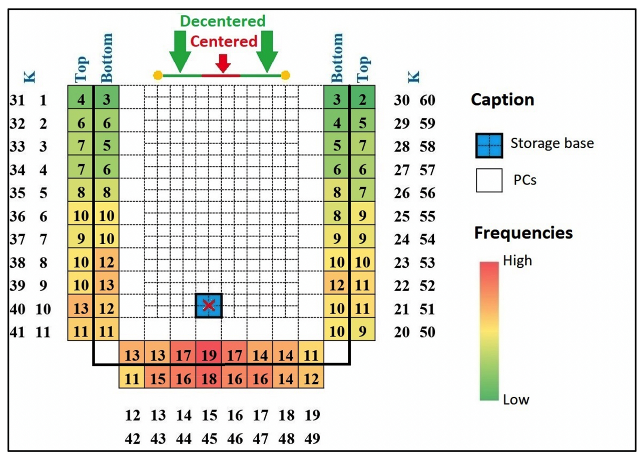

Figure 5: Storage assignment and position of the storage base for a random instance with *normal* distribution for picking frequencies, $|P|$ = 10 and $|Q|$ = 12. The numbers on the PCs are approximated picking frequencies.

base is more centred on the P axis to reflect the fact than it is worth to be relatively close to a higher number of products that similar picking frequencies. Looking at the average position on the Q axis, it is still convenient to remain as low as possible in the corridor.

6.2.2 *Overall Layout Optimization.* In this section we study the position of the storage base for different layouts and frequency distributions for the products.

Given the values of P and Q, we follow the procedure *OptOverallLayout* (Algorithm 2) and we consider all the feasible positions of the base (coordinates b_p, b_q) and calculate for each of them the relative optimal storage assignment. We report the storage base location generating the lowest ergonomic strain.

To evaluate the optimal position of the base with respect to different layouts, we introduce the following indicators:

$$b_{p(\%)} = \frac{1-(b_p-2.5)}{\frac{|P|}{2}-2.5}\cdot 100$$

$$b_{q(\%)} = \frac{b_q-2.5}{|Q|-3.0}\cdot 100$$

Note that in this section we consider distances in terms of number of PCs instead of meters, since we report percentages of deviations.

The indicators above take the value 0 when $b_p = \frac{|P|}{2}$ and $b_q = 2.5$, which means the storage base is in the centre-bottom position. We take this location as a reference since it is a promising position, according to the results of [8]. A value $b_{p(\%)} = 100$ means that the base is completely on the left with respect to the P axis ($b_p = 2.5$). Note that we only consider the range $[2.5, \frac{|P|}{2}]$ for b_p since higher values would generate mirror solutions with respect to those generated. A value $b_{q(\%)} = 100$ on the other hand means that the base is located as high as possible in the corridor: $b_q = |Q| - 0.5$.

Tables 2, 3 and 4 summarize the results over the datasets considered. The tables report the average percentage deviation from $b_p = \frac{|P|}{2}$ and $b_q = 2.5$ ($b_{p(\%)}$,$b_{q(\%)}$) for the different instance sizes of each database, both for the solution with a centred base ($b_p = \frac{|P|}{2}$) as suggested in the previous literature, and for the case when b_p is free to vary. Table 2 reports the averages over all possible feasible layout (values of $|P|$ and $|Q|$) of each instance set, while Table 3 reports the average results for narrow corridors (smallest possible value of $|P|$) and Table 4 reports the average results for wide corridors (largest possible value of $|P|$). It has been chosen to consider narrow corridors because they normally represent the most efficient solution and wide corridors because, although they are likely to be inefficient, they are still possible in real settings.

An analysis of Table 2 suggests that allowing the base to be off-centred can be convenient in terms of optimized layout. Indeed, this is intuitively reasonable since we give one more degree of freedom to the system. It is interesting to observe that moving the base on the P axis is particularly effective on small/medium instances with unbalanced distributions, such as Random-exponential. The benefits are less obvious once the picking frequency of products are very similar to each other (instances from [8]). It is also interesting to notice how also the position of the storage base on the Q axis changes once the position on the P axis is free. This suggests that substantially different storage assignments are generated with respect to those generated with $b_p = \frac{|P|}{2}$.

Tables 3 and 4 confirm the trends already emerged in Table 2. It is interesting to observe that in case of narrow corridor (Table 3) moving the base by the side as much as possible is generally convenient, although the position on the Q axis does not vary, and the overall gain in ergonomic strain is marginal. On the other hand, when wide corridors are examined (Table 4) the optimal position of the storage base is always at the bottom, while moving it towards the left corner (sometimes only marginally) improves the quality of the solutions, sometimes substantially.

When comparing the costs of the best solutions across the tables, one can observe how the narrow corridor is consistently the most convenient layout, with costs remarkably smaller than those of the wide corridor.

The ergonomic strain is diminished on average by 1.44% by allowing an off-centred storage base, with picks up to 10.36% on some instances. This suggests that the idea could bring concrete benefits once implemented, both in terms of health of the pickers, and economic as a both direct (travel times are correlated to strains, [8]) and indirect (less workers injuruies) side effect.

Table 2: Average best storage base deviation from $b_p = \frac{|P|}{2}$ and b_q=2.5 and ergonomic strain all the feasible corridor layouts, namely 2 for 30 PCs, 10 for 60 PCs and 20 for 100 PCs.

Dataset/ Distr.	PCs	Nr Inst	$b_p = \frac{\lvert P\rvert}{2}$		b_p free		
			$b_{q(\%)}$	eqn (1)	$b_{p(\%)}$	$b_{q(\%)}$	eqn (1)
[8]/	30	20	0.00	521.43	0.00	0.00	521.43
Unif	60	20	7.50	1683.42	10.02	7.58	1683.15
(small)	100	10	5.38	3616.53	36.28	6.14	3606.26
Random/	30	40	0.00	436.47	100.00	0.00	413.78
Exp	60	20	0.43	1211.87	87.34	0.74	1166.80
	100	12	2.30	2790.80	71.73	3.50	2734.69
Random	30	40	0.00	490.66	79.38	0.00	486.76
Norm	60	20	4.18	1521.29	35.43	4.56	1516.62
	100	12	6.69	3748.05	29.65	7.32	3741.71
Random	30	40	0.00	459.03	100.00	0.00	445.84
Unif	60	20	2.45	1377.86	61.39	3.21	1362.89
(large)	100	12	4.78	3333.50	43.87	5.58	3316.68
Real	30	28	0.00	65.89	100.00	0.00	62.76
Exp	60	14	1.37	189.21	81.99	1.43	184.01
	100	8	3.17	446.15	62.61	4.69	440.67

Table 3: Average best storage base deviation from $b_p = \frac{|P|}{2}$ and b_q=2.5 and ergonomic strain for the narrowest possible corridors, with $|P|$=7 and $|Q|$=6 for 30 PCs, $|P|$=6 and $|Q|$=14 for 60 PCs and $|P|$=6 and $|Q|$=24 for 100 PCs.

Dataset/ Distr.	PCs	Nr Inst	$b_p = \frac{\lvert P\rvert}{2}$		b_p free		
			$b_{q(\%)}$	eqn (1)	$b_{p(\%)}$	$b_{q(\%)}$	eqn (1)
citec10/	30	20	0.00	500.12	0.00	0.00	500.12
Unif	60	20	34.78	1352.77	0.00	34.78	1352.77
(small)	100	10	37.21	2654.26	100.00	37.21	2652.72
Random/	30	40	0.00	421.71	100.00	0.00	405.91
Exp	60	20	4.35	1026.24	100.00	7.39	1014.17
	100	12	32.17	2141.97	100.00	32.17	2128.24
Random/	30	40	0.00	470.39	100.00	0.00	466.92
Norm	60	20	26.52	1238.19	100.00	26.52	1235.38
	100	12	37.21	2738.71	100.00	37.21	2736.99
Random/	30	40	0.00	439.95	100.00	0.00	431.03
Unif	60	20	22.61	1129.91	100.00	23.04	1126.69
(large)	100	12	36.82	2455.17	100.00	36.82	2453.32
Real	30	28	0.00	63.60	100.00	0.00	61.30
Exp	60	14	13.66	159.86	100.00	14.29	158.09
	100	8	36.63	338.13	100.00	36.63	336.39

Table 4: Average best storage base deviation from $b_p = \frac{|P|}{2}$ and $b_q = 2.5$ and ergonomic strain for the widest possible corridors, with $|P|$=9 and $|Q|$=5 for 30 PCs, $|P|$=24 and $|Q|$=5 for 60 PCs and $|P|$=22 and $|Q|$=5 for 100 PCs.

Dataset/ Distr.	PCs	Nr Inst	$b_p = \frac{\lvert P\rvert}{2}$		b_p free		
			$b_{q(\%)}$	eqn (1)	$b_{p(\%)}$	$b_{q(\%)}$	eqn (1)
[8]/ Unif (small)	30	20	0.00	542.73	0.00	0.00	542.73
	60	20	0.00	1925.60	5.26	0.00	1925.25
	100	10	0.00	4082.57	6.15	0.00	4078.99
Random/ Exp	30	40	0.00	451.22	100.00	0.00	421.66
	60	20	0.00	1327.16	42.63	0.00	1306.84
	100	12	0.00	3053.25	17.95	0.00	3041.01
Random/ Norm	30	40	0.00	510.93	58.75	0.00	506.61
	60	20	0.00	1721.62	11.05	0.00	1717.60
	100	12	0.00	4269.35	5.56	0.00	4265.51
Random/ Unif (large)	30	40	0.00	478.11	100.00	0.00	460.65
	60	20	0.00	1546.37	23.68	0.00	1536.57
	100	12	0.00	3744.80	9.40	0.00	3739.58
Real/ Exp	30	28	0.00	68.19	100.00	0.00	64.22
	60	14	0.00	208.03	24.81	0.00	206.60
	100	8	0.00	490.85	6.41	0.00	490.02

7 CONCLUSIONS

Given a set of products with the respective characteristic and picking frequencies, we consider the optimization of the layout of U-shaped storage areas in terms of the expected ergonomic strain suffered by the human pickers. We especially focused on the role of the location of storage base, extending the results available in the current literature and showing that an asymmetric positioning of the latter can lead to more optimized solutions. Experimental results on artificial and real-world instances clearly show that asymmentric configurations can enhance the efficiency, leading to the conclusion that the location of the storage base plays an important factor in the optimization process.

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