

Economic rationale for determining the optimal layout of racks and aisles in enclosed warehouses for single piece cargo

Daurenbek Ilesaliev^{1*}, *Rysty Sartova*², *Aleksandr Svetashev*¹, *Azizbek Ismatullaev*¹, and *Jamol Shihnazarov*¹

¹Tashkent State Transport University, Uzbekistan

²al-Farabi Kazakh National University, Kazakhstan

Abstract. The purpose of this study is to substantiate the effectiveness of the selection of options for the placement of racks and aisles in covered warehouses for single-piece cargo. As part of the study, the storage capacities were determined, considering the peculiarities of storage and movement of such goods. To achieve this goal, an algorithm was proposed for selecting the effective placement of aisles and racks in the warehouse. This algorithm considers various factors, such as warehouse capacity, interaction with various modes of transport and reduction of downtime of vehicles waiting for loading and unloading operations at these warehouses. The practical significance of this research lies in the fact that its results make it possible to improve the interaction of various modes of transport through the warehouse, increase the capacity of warehouses and reduce downtime of vehicles waiting to perform operations in these warehouses. This helps to reduce time costs, increase the efficiency and efficiency of warehouses, as well as improve the overall logistics chain of transportation of packaged goods.

1 Introduction

The transformation of cargo flows and the efficiency of warehouses in the cargo transshipment zone between different modes of transport play an important role in the technological scheme of cargo delivery. Optimal equipment and organization of intermediate warehouses in transport significantly affect the effectiveness of this scheme [1-9].

With each passing day, the size of warehouses is increasing, and this entails an increase in operating costs for moving goods in transshipment warehouses. Such costs have a negative impact on customers, as they are forced to cover these costs by increasing the prices of their products.

* Corresponding author: ilesaliev@mail.ru

2 Methods

Given that warehouse buildings are expensive structures, it is advisable to fill them with cargo as much as possible. To do this, it is necessary to maximize the internal volume of the warehouse and place the maximum number of cargo storage units (racks) along, across and in height. It is for this purpose that the methodology for choosing the optimal ratio between the warehouse capacity and the loader mileage is being developed. Usually, racks and aisles in warehouses for single-piece cargo are located perpendicular to each other, as shown in figure 1.

Thus, the efficiency of transshipment warehouses is important for optimizing cargo flows and reducing costs. The maximum use of the internal volume of the warehouse and the optimal placement of racks contribute to increasing efficiency and saving resources when storing and moving goods in the warehouse.

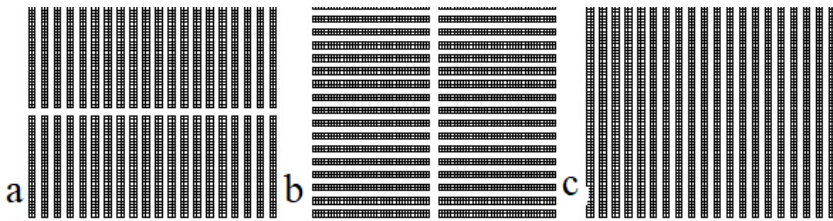


Fig. 1. Traditional arrangement of racks and aisles.

The optimal placement of racks in the warehouse has its advantages in terms of capacity, however, such a traditional layout is also associated with some disadvantages, including an increase in operating costs associated with the movement of loading and unloading equipment from the loading and unloading area to the cargo storage areas [1-4].

However, foreign scientists have proposed to radically change the layout of the racks and longitudinal aisles in order to significantly increase the efficiency of the warehouse [2-3, 7]. One such scheme is a V-shaped placement, which includes a curved cross passage. This makes it possible to reduce the distances that the loader must travel from the loading and unloading area to the cargo storage areas, thanks to the "Euclidean advantage" (see Figure 2, a). However, this scheme has one drawback: the loader needs to turn at a steep angle when entering the lower part of the warehouse. To eliminate this drawback, it is proposed to rotate the lower part perpendicular to the main part of the warehouse (see Figure 2, b). This approach creates favorable conditions for turning the loader when moving to the storage areas of packaged goods.

Such change in the layout of the racks allows you to reduce the time spent on moving goods and improve the overall efficiency of the warehouse. Optimization of the spatial organization and consideration of the features of the movement of loaders contribute to the optimal use of the internal volume of the warehouse and increase productivity.

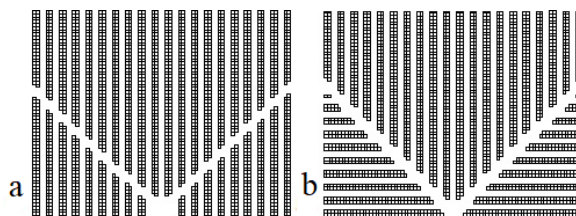


Fig. 2. V-shaped arrangement of passages (a), Christmas tree shelving arrangement (b).

In Figure 3, the dotted line denotes the "Euclidean" distance, while the solid line denotes the "Manhattan" distance.

The "Euclidean" distance, also known as a straight line or a geometric distance, is the shortest distance between two points in space. It is measured in a straight line, straight from one point to another, as if you had drawn a thread between these points.

The "Manhattan" distance, also known as the city distance or L-norm, is calculated as the sum of the absolute differences between the coordinates of two points. It got its name due to the geometry of streets in Manhattan, where movement between two points is carried out along perpendicular streets and then along horizontal or vertical streets.

Thus, the dotted line in Figure 3 represents the direct distance between the points, and the solid line shows the path that should be traversed taking into account perpendicular and horizontal/vertical movements (Manhattan distance). Both types of distances are used to evaluate the efficiency of moving loaders in a warehouse and to select optimal shelving layouts.

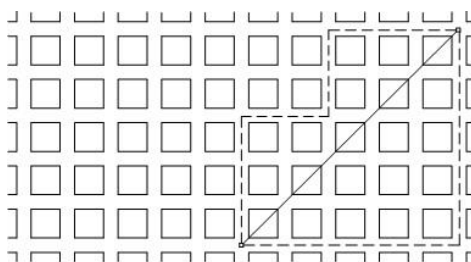


Fig. 3. In the metric of city blocks, the lengths of the dotted lines are equal (L). In Euclidean geometry, a solid line has a length ($L/\sqrt{2}$) and represents the only shortest path.

The distance that the loader must travel from the loading and unloading area to the storage place of the tare-piece cargo can be determined using the formula proposed by Herman Minkowski.

The Minkowski formula is a way of calculating the total distance based on the "Euclidean" distance and the "Manhattan" distance. It combines these two types of distances into one common value, taking into account the differences in the movement of the loader in the warehouse.

$$d_i = \left[\sum_{k=1}^n |x_k - y_k|^q \right]^{\frac{1}{q}}, \tag{1}$$

The above family of distances includes

- when $q = 1$ – "manhattan distance";
- when $q = 2$ is the Euclidean distance.

Using the Minkowski formula, it is possible to determine the optimal distance that the loader must travel, considering both rectilinear movement (Euclidean distance) and movement along perpendicular and horizontal/vertical paths (Manhattan distance). This allows you to choose the most effective layout of racks and longitudinal aisles in the warehouse.

For example, for Euclidean distance, the formula looks like this:

$$d_i(x, y) = \sqrt{\sum_{k=1}^n (x_k - y_k)^2} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}, \tag{2}$$

For the Manhattan distance, the distance is determined by the following formula:

$$d_i(x, y) = \sum_{k=1}^n |x_k - y_k| = |x_1 - x_2| + |y_1 - y_2|, \quad (3)$$

2.1 Determination of the capacity of the warehouse of tare-piece cargo.

The capacity for a warehouse of tare-piece cargo is determined by the formula:

$$R = x \cdot y \cdot z, \quad (4)$$

where x is the number of pallets located across the width of the warehouse building;
 y is the number of pallets along the length of the storage area racks;
 z is the number of tiers in height.

The maximum number of x racks in width is determined by the formula:

- for a traditional warehouse:

$$x = 2 \cdot \varepsilon \left\{ \frac{B \cdot \xi_c - B_0}{B_m + 2 \cdot (b + \lambda)} \right\}, \quad (5)$$

- for a warehouse with a V-shaped aisle arrangement:

$$x = 2 \cdot \varepsilon \left\{ \frac{B \cdot \xi_c - B_0 - 2 \cdot (b + \lambda) \cdot \cos \alpha}{B_m + 2 \cdot (b + \lambda)} \right\}, \quad (6)$$

where 2 is the number of racks in a section consisting of 2 racks and a passage between them;

B – width of the span of the warehouse building;

ξ_c – the coefficient of the length of the racks, taking into account that a part of the length of the warehouse can be occupied by a receiving expedition (for the variant shown in Figure 3 b, $\xi_c = 0.8$ is taken as a first approximation, showing that it occupies 20% of the length of the building; if the receiving expedition is located along the entire length of the warehouse, as shown in Figure 3 a, from the side of the approach of motor transport and rail transport, accept $\xi_c = 1$);

B_0 – the part of the span width of a warehouse building that cannot be occupied by racks (includes the width of the building columns, gaps from the column to the extreme rack or cargo protruding from it, etc.);

B_m – the width of the longitudinal passage, depending on the technical parameters of the loader, m;

b – the length of a standard pallet is 1200×800 mm, m (pallets are recommended to be installed with a long side of 1200 mm into the depth of the rack to obtain the largest storage capacity);

λ – the gap between the pallets in the double-sided rack and between the pallet and the rack structure, m;

$\varepsilon\{\dots\}$ – notation of the integer part of the number resulting from performing actions in parentheses (rounding down an integer).

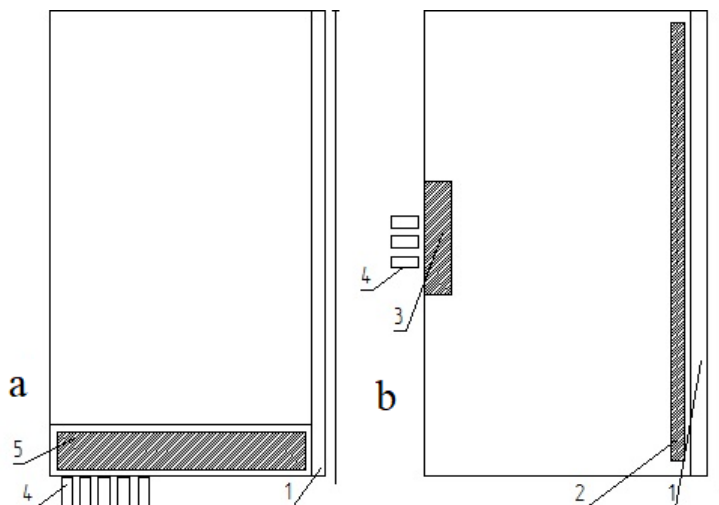


Fig. 4. Options for the location of the receiving and sending expedition in the warehouse: at the end (a), along the warehouse (b)

The number of pallets along the length of the shelving service by lifting and transport equipment is determined by the formula:

- for a traditional warehouse:

$$y = 3 \cdot \varepsilon \left\{ \frac{L \cdot \xi_c - n_{pr} \cdot B_{pr}}{2,8} \right\}, \tag{7}$$

- for a warehouse with a V-shaped aisle arrangement:

$$y = 3 \cdot \varepsilon \left\{ \frac{L \cdot \xi_c - B_{pr}}{2,8} \right\}, \tag{8}$$

where 3 is the number of 1200×800 mm pallets that fit into a standard cell with a length of 2800 mm when laying them with a side of 1200 mm into the depth of the racks (such an installation of pallets allows you to get the capacity of the racks by 10-15% more compared to installing pallets with a side of 800 mm into the depth of the racks);

L – length of the warehouse building, m;

n_{pr} – the number of cross passages along the length of the warehouse (passages are designed through 40-50 m; if cross passages are provided through the walls in 1-2 tiers, $n_{pr} = 0$);

B_{pr} – width of aisles in the warehouse, m;

2,8 m is the cell length of a standard frame rack;

The number of tiers in the height of the storage area for an existing warehouse building is determined depending on the useful height H and the height of the transport package according to the formula:

$$z = \varepsilon \left\{ \frac{H - 0,5 - C_{ya}}{C_{ya}} \right\} + 1, \tag{9}$$

where 0.5 is the gap between the upper load in the rack and the bottom of the overlap trusses (used for installation of pipelines, lighting devices, etc.);

C_{ya} – the height of the tier, m, is determined by the formula: $C_{ya} = 0,15 + c + e$ (where 0.15 m is the height of a flat wooden double-lined pallet, c is the height size equal to the thickness of the longitudinal beam of the frame rack and the gap between the load and the bottom of this beam of the next tier in height, take $e = 0.2 - 0.3$ m);

1 – additional upper tier.

If you know the lifting height of the loader H_p , then the number of tiers in height is calculated by the formula:

$$z = \mathcal{E} \left\{ \frac{H_p - 0,5}{C_{ya}} \right\} + 1, \quad (10)$$

The calculation of the storage area parameters for schemes with a Christmas tree arrangement of racks is calculated similarly to a traditional warehouse, which forms two rectangles with a length (L) and a width ($B/2$).

2.2 The choice of rational placement of racks and aisles.

In most of the existing warehouses, stacked storage of single-piece cargo is used. However, this method of storage has some disadvantages, such as limited storage height, difficulties in accounting for the location of goods, the inability to store a variety of goods and other factors that reduce the productivity of the warehouse and the organization of transportation.

Due to the listed disadvantages, it is recommended to use racks when upgrading warehouses with stacked cargo storage. When choosing the placement of racks and aisles for warehouse equipment with frame racks, three options can be considered: traditional placement, V-shaped placement and placement in the shape of a Christmas tree.

The traditional placement of racks implies straight aisles between the racks, which is the most common and familiar approach.

The V-shaped placement of the racks includes a curved cross passage, which reduces the distances that the loader must travel from the loading and unloading area to the cargo storage areas. This can improve the efficiency of the warehouse.

The placement of the racks in the shape of a Christmas tree suggests turning the bottom of the racks at right angles to the main part of the warehouse. This creates favorable conditions for the turns of the loader when moving to the storage places of single-piece cargo.

The choice of the optimal placement of racks and aisles depends on the characteristics of the warehouse, the types of cargo and the efficiency of the work to be achieved. Each of these options has its advantages and can be applied to improve the organization of storage and increase warehouse productivity.

The option of placing racks and aisles in the warehouse should be chosen while ensuring a higher integral effect:

$$U_{\text{int}} = \frac{U_i - U_{\text{addi}}}{E} - K_{\text{addi}} \rightarrow \max, \quad (11)$$

where U_i is economic effect of reconstruction, thousand sum;

U_{addi} – additional operating costs, thousand r sum;

K_{addi} – additional capital investments, thousand sum;

E – discount rate.

The block diagram of the algorithm for choosing the option of effective placement of racks and aisles is shown in figure 5.

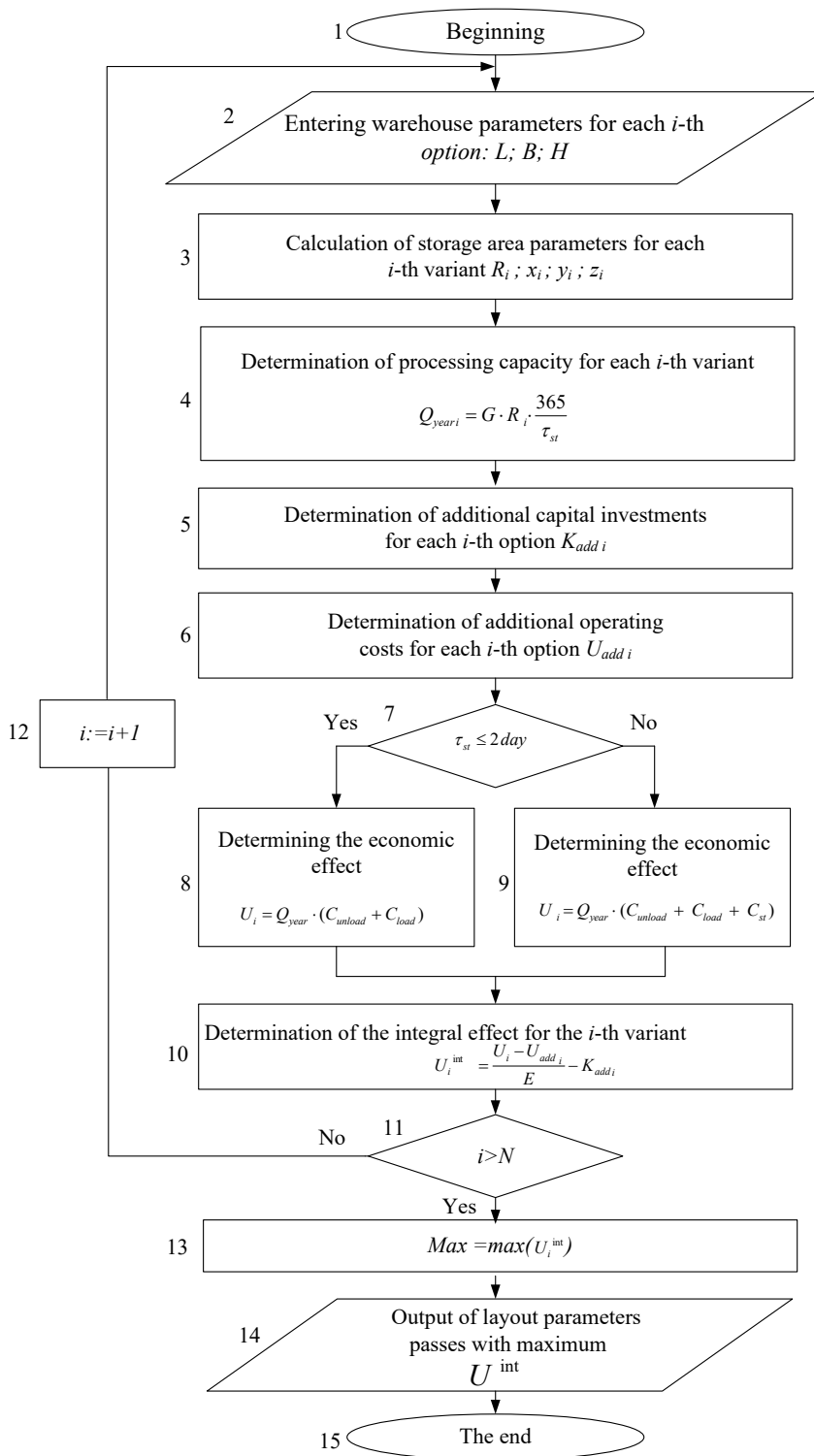


Fig. 5. Block diagram of the algorithm for selecting the effective placement of aisles and racks in the warehouse

Description of the algorithm flowchart:

- 1 – The beginning of the process of choosing an effective option.
- 2 – Entering parameters of an existing transshipment warehouse with parameters L, B, H for each i -th variant.
- 3 – Calculation of storage area parameters for each i -th variant. Determining the number of shelves by width x_i , length y_i and height z_i , as well as the total capacity R_i warehouse.
- 4 – Determination of the new processing capacity of the transshipment warehouse Q_{year} , for each i -th option;
- 5 – Determination of additional capital investments K_{addi} for each i -th option;
- 6 – Determination of additional operating costs \mathcal{E}_{add} for each i -th option;
- 7 – Depending on the period of storage of goods in the warehouse, the economic effect is determined (2 days is the period of free storage of goods in transshipment warehouses in accordance with the tariff guide Price List 10-01).
- 8 – Calculation of the economic effect \mathcal{E}_i from the processing of tare-piece cargo without taking into account the cost of storage for each i -th option;
- 9 – Calculation of the economic effect \mathcal{E}_i from the processing of tare-piece cargo, taking into account the cost of storage for each i -th option;
- 10 – Determination of the integral effect for each i -th variant \mathcal{E}_i^{int} ;
- 11 – Checking that all variants of warehouse schemes are calculated;
- 12 – Sorting through all variants of transshipment warehouse schemes;
- 13 – Determination of the maximum integral effect \mathcal{E}_i^{int} ;
- 14 – Output of parameters of the layout of passages with the maximum integral effect \mathcal{E}_i^{int} ;
- 15 – The end of the process of choosing an effective option.

When designing or reconstructing an existing warehouse, after determining its possible capacity in pallets R , determine the new processing capacity (annual cargo flow in pallets) of the transshipment warehouse:

$$Q_{year} = G \cdot R \cdot \frac{365}{\tau_{st}}, \text{ t/year} \quad (12)$$

where τ_{st} – is cargo storage period in the warehouse, day.

G – the mass of the transport package, t.

The economic effect of the reconstruction of the transshipment warehouse is determined by the formula:

$$U = Q_{year} \cdot (C_{unload} + C_{load} + C_{st}), \text{ mln.sum / year} , \quad (13)$$

On conditions:

$$C_{st} = \begin{cases} 0, & \text{if } t_{st} \leq 2 \text{ day} \\ C_{st}, & \text{if } t_{st} > 2 \text{ day} \end{cases}, \quad (14)$$

where Q_{year} is annual cargo flow, pallets/year;

C_{unload}, C_{load} – mechanized unloading and loading of pallets of tare-piece cargo, respectively, sum/pallets;

C_{st} – the fee charged to customers for the storage of pallets with tare-piece cargo for one day, sum/pallets;

3 Discussion

The method of choosing the layout of racks and aisles, based on the relationship between the parameters of the warehouse and mathematical models, allows us to estimate the increase in the processing capacity of the warehouse of packaged goods by reducing the mileage of the loader and changing the capacity of the warehouse. This reduces operating costs and ultimately has a positive effect on customers.

Calculations on the main parameters of storage areas used in the methodology are quite simple, but they allow you to quickly consider various options for shelving placement. These calculations may include parameters such as warehouse area, storage height, aisle width, load-lifting capacity of racks and other factors affecting warehouse efficiency.

The technique allows taking into account the "Euclidean advantage" when choosing the layout of racks and aisles. That is, it focuses on reducing the distance that a loader must travel to move cargo. This can be achieved by optimizing the logic of shelving placement, creating optimal ways of moving and taking into account the flow of work in the warehouse.

The methodology allows you to compare different options for the placement of racks and aisles and assess their impact on the processing capacity of the warehouse. It helps to make an informed decision when choosing the optimal placement scheme, taking into account economic and operational factors.

The implementation of the proposed methodology can contribute improving the efficiency of the warehouse, reducing the mileage of the loader, optimizing the use of space and increasing the capacity of the warehouse. This leads to lower operating costs and improved customer service.

References

1. A. Donenbaykyzy Kassymzhanova, M. Kenesovich Ibatov, O. Temirgalievich Balabayev, Bakytzhan Serikovich Donenbaev, Daurenbek Ikhtiyarovich Ilesaliyev. Experimental Study of Maximum Stresses in the Stationary Hoist Design in the Ansys Software Environment. Communications - Scientific Letters of the University of Zilina **24(4)**, B310-B318 (2022) DOI: 10.26552/com.C.2022.4.B310-B318
2. K.R. Gue, G. Ivanovich, R.D. Meller, A warehouse with a single loading with several receiving and depositing points and non-traditional passages. Transport research. Part E, **48**, 795-806 (2012)
3. K.R. Gyu, R.D. Meller, Configurations of aisles for warehouses with a single load. Transactions IIE, **3**, 171-182 (2009)
4. D. Ilesaliev, J. Kobulov, R. Tursunkhodjaeva, M. Tashmatova, Research and Selection of Rational Parameters of a Refrigerated Container Terminal. Lecture Notes in Networks and Systems, **510**, 829–840 (2023)
5. I.I. Ilesaliev, S.G. Makhmatkulov, S.R. Abdvakhitov, *Peculiarities of container terminal functioning in delivery chains*. IOP Conference Series: Materials Science and Engineering, **918(1)**, 012043 (2020)
6. O. Ozturkoglu, K.R. Gue, R.D. Meller Optimal warehouse solutions with a single load for operations with one team. Transactions IIE, **44**, 459-475 (2012)
7. L.M. Paul, R.D. Meller, K.R. Gyu Optimization of passages for fish bones for operations with two teams in the warehouse. Naval Research Logistics, **56**, 389-403 (2009)
8. M. Shakhobiddin, I. Daurenbek, Stage of development of the railway section. International Journal of Innovative Technology and Exploring Engineering, **9(1)**, 3239–3245 (2019)