

SESSION A:

EARTH MOVING AND TRANSPORTATION MACHINERY

Comparative analysis of rack layouts according to the storage unit placement method

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ABSTRACT

The paper presents a comparative analysis of two selective pallet rack configurations based on the storage unit placement method, using the same rack orientation within the warehouse space. Selective pallet racks are simple, efficient, and widely used systems for storing palletized goods. They provide direct and unobstructed access to every individual pallet at any time. The storage unit was defined, and the sizing of the beams and upright frames was performed. Appropriate storage and retrieval equipment was selected. The rack layout in the warehouse was determined in accordance with warehouse system design principles. Adequate structural components were chosen, and the total capacity of the rack warehouse was calculated. Within the comparative analysis of selective racking solutions in the planned warehouse space, designs with both transverse and longitudinal storage unit placement were considered. The design focus was on increasing warehouse capacity and reducing rack construction costs.

KEYWORDS

Warehouse, Pallet Rack, Forklift.

1. INTRODUCTION

Existing storage systems have the primary task of efficiently storing and distributing a large quantity of goods in the shortest possible time in a defined space.

Pallet racking storage system consists of the three basic elements: racks, pallets, and forklifts or handling equipment. Each of them is selected based on materials being stored, the storage requirements, operating and positioning systems and the applied management [1]. In general, spatial frame structure of the pallet racking system is made of the side frames and the horizontal beams, usually made of thin-walled cold-formed profiles, to make the pallet rack configuration.

Selective pallet racking systems are the most common. They can accept a large number of different unit loads and allow direct access to the pallets [2]. As an upgrade to standard racks, a double deep pallet racking is used. With this solution, each pallet shelf holds two rows of pallets instead of one. The mobile pallet racking variant maximizes storage capacity by eliminating multiple static aisles. Efficient solutions such as drive-in and drive-through racking systems are in use. Pallet flow racking systems have been developed that use gravity or wheel and roller systems to transfer and store pallets.

The primary components of all these racks include vertical elements (such as columns), horizontal elements (such as front and rear beams) and horizontal and/or diagonal braces [3]. Elements that provide the stable spatial structure are an essential part of every type of rack. They are categorized into basic and additional elements. The basic elements are: vertical frames, horizontal beams, baseplates with anchors, and spacers.

A complete analysis of the rack structure and each component is achieved by using the determined structural properties and applying European standards and regulations. [4-6].

2. DESIGN OF SELECTIVE PALLET RACKING SYSTEMS

This storage system has three basic elements: racks, pallets, and forklifts or handling equipment. Each of them is adopted based on the materials being stored, storage requirements, working and positioning systems, and the management that is being applied [7]. Since storage systems represent a large capital investment, it is necessary to properly define the layout and configuration of the storage equipment [8].

2.1. Defining a Storage Unit

When designing a warehouse, the first step is to define the storage unit, i.e., the corresponding pallet with its load. Defining the storage unit provides information regarding its length, width, height, shape, tolerances, and total weight.

2.2. Dimensioning of Storage Unit Supports

The dimensioning of the storage unit supports is carried out according to the load of the pair of the supports. The length of the storage unit supports is determined by the number of storage units in one bay, including the required clearances, defined by regulations and standards [9-10]. The aforementioned clearances are present between adjacent storage units, as well as between the outermost points of the storage units and the upright frames. In addition to the dimensions of the storage unit, the method of its placement also has an undeniable impact on determining the beam (support) length. Storage unit placement can be: transverse and longitudinal.

2.2.1. Racking Beam Length

Based on the sum of the prescribed clearances defined according to [7], both between the storage units and the upright frames, and between the storage units themselves, the beam length is adopted as a standard dimension defined by the manufacturer, which closely matches the calculated value.

2.2.2. Load Capacity of a Pair of Horizontal Beams

The load capacity of a pair of horizontal beams is determined by the number and weight of the storage units that need to be stored in one bay. As a product of these two parameters, the adopted load capacity of the pair of horizontal beams must be equal to or greater than the calculated value. Then, according to the length of the beams and the required load capacity, the first larger standard profile of the storage unit beam is adopted with defined characteristics equal to or greater than the calculated ones. The defined characteristics relate, in addition to the basic characteristics, to the geometry of the adopted profile.

2.3. Dimensioning of the Upright Frame

When dimensioning a vertical frame, its width, height of one floor and total height are determined, according to the recommendations in accordance with [7,8].

2.3.1. Upright Frame Width

The width of the upright frame is influenced by the method of storage unit placement and the available transport and handling equipment, so the width of the vertical frame is equal to the shortest dimension of the storage unit at the base that enters the rack in the case of transverse stacking. If the stacking is longitudinal, the width of the vertical frame is 50 mm ÷ 100 mm shorter than the length of the storage unit. In this case, its ends have an overhang of at least 50 mm over the beam.

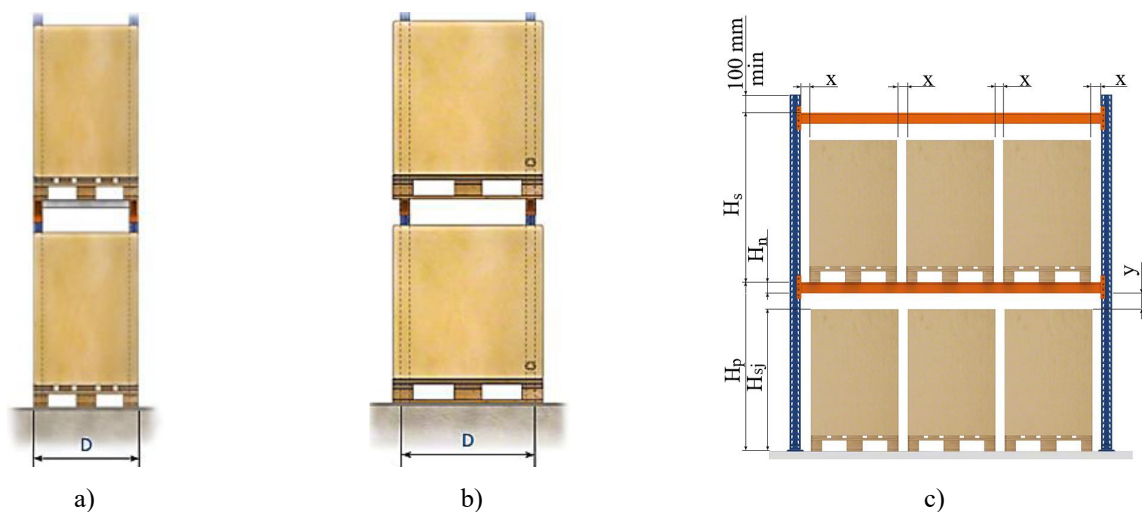


Figure 1: View of the storage unit layout: a) transverse, b) longitudinal, c) upright frame dimensions

Figure 1 illustrates a parallel view of the position of the storage unit in the case of transverse and longitudinal stacking. Dimension D in the figure indicates the width of the frame and the position of the storage unit during placement.

The dimensions indicated in Figure 1 are: H_{sj} – height of the storage unit, H_p – height from the base to the first floor, H_s – height of one floor, H_n – height of the horizontal storage unit beam, x – horizontal clearances between storage units, and between uprights and storage units, and y – vertical clearance between the top of the storage unit and the horizontal beam.

When designing, in order to achieve optimal load storage, proper placement is extremely important, especially when stacking longitudinally, because in the case of improperly distributed cargo, it can tip over.

2.3.2. Floor Height or Pitch

The height of the rack floor is determined by the height of the storage unit and the required clearances in the vertical direction defined according to [7]. It is necessary to pay attention to the position of the first floor when determining the total height of the vertical frame, whether it is located directly on the floor or is raised to a specific height above it. The resulting calculated value of the floor height must be divisible by the perforation pitch of the vertical frame column. Based on the data obtained, it is necessary to adopt a standard beam pitch value according to the relevant manufacturer's catalogue.

2.3.3. Vertical Frame Height and Column Profile

The height of the vertical frame is determined by the height of the storage unit, the necessary clearances between the storage unit and the beam, and the beam height, and it is definitely limited by the available height of the storage space. Figure 1 c) shows all the dimensions by which the vertical frame is fully dimensioned. The key elements that influence the dimensioning of the frame are: the height of the storage space, the height of the storage unit, the position of the first floor, and the capabilities of the material handling equipment.

Based on the number of floors and the number of storage units in the bay, the maximum load capacity of the vertical frame can be determined. The load capacity of the vertical frame is calculated as the sum of the load capacity of each bay, or as the product of the load capacity of one bay/floor and the number of floors, excluding the load capacity of the one located directly on the floor. After that, it is possible to adopt the appropriate standard column profile of defined dimensions and shapes.

2.4. Dimensioning of Cross Beams of a Storage Unit

In the case of transverse placement of a storage unit, in addition to dimensioning a pair of horizontal beams, it is also necessary to dimension the transverse supports of the storage units according to their load capacity. These supports are placed in a direction perpendicular to the horizontal beams and are appropriately supported by a pair of horizontal supports.

According to the above, a minimum of two cross-beams, usually of rectangular cross-section, with defined characteristics, are always adopted for one storage unit. Therefore, the height of the cross-beam must not be greater than the cross-section height of the horizontal beam of the storage unit. When it comes to longitudinal stacking, cross-beams are generally not used, except in the case of poor quality pallets. Most often, the storage unit is supported by a pair of horizontal beams via the pallet sleds, so there is no possibility of collapse through the rack structure or pallet breakage.

2.5. Definition of the Material Handling Devices

Rack warehouses are most often served by forklifts and represent the most developed form of material handling equipment, which, in addition to the ability to actively pick up and place loads, also have the ability to stack loads vertically.

2.6. Racking Layout in the Storage Space

When designing the layout of selective pallet racks, it is necessary to fully define three conditions necessary for the implementation of the design: defining the storage unit, selecting the material handling equipment, and defining the storage space. In order to achieve maximum utilization of the storage space and work efficiency, in addition to the previously covered conditions, it is necessary to take into account certain design rules. These rules are reflected in the following [11]: A single-row rack should be placed against the wall of the storage space; Placing racks in the same space in two different directions should be avoided, as this wastes a lot of space for manipulation and intersects transport routes; Racks should always be placed along the longer side of the intended storage space, which results in fewer long corridors, reduces transport aisles, and increases the economic feasibility of the racks; Corridors should not be placed along the perimeter of the walls of the space.

2.7. Total Capacity of the Rack Warehouse

After calculating and adopting adequate racking structure components, it is possible to determine the achieved warehouse capacity for different concepts of storage unit placement concepts. To determine the total warehouse capacity, it is necessary to define: the number of storage units per bay, the number of the identical bays, the number of floors and the number of continuous identical racking rows.

The number of storage units per bay differs for cases of transverse and longitudinal placement, primarily due to the dimensions of the storage unit. Also, the load of the pair of horizontal beams in one bay and the load of the vertical frame have a significant influence.

A bay is defined as the space between adjacent vertical frames and adjacent horizontal beams, in which a certain number of storage units are stored, most commonly two or three.

The number of floors is the number of bays in the height of the rack, excluding the one located directly on the basement, while the section is a vertical module located between adjacent vertical frames. A section is defined by the sum of the heights of the individual bays, including the one located on the basement.

The number of continuous identical racking rows in the case of selective pallet racks can be configured as a single-row or a double-row. In this case, a single-row rack is defined as a row of bays accessible from one working aisle. Double-row racks are a parallel row of two single-row racks whose backs are connected into one whole by spacers. Compared to the single-sided racks, the double-sided racks are accessible from two parallel operating aisles. The total capacity of the rack storage is determined according to the expression:

$$Q_u = N_s \cdot N_p \cdot N_r \cdot N_k \quad (1)$$

where:

N_s – number of storage units per bay,

N_p – number of identical bays,

N_r – number of continuous identical racking rows, and

N_k – number of floors.

3. COMPARATIVE ANALYSIS

The planned storage space has the following dimensions: length 34500 mm, width 28500 mm, height 7500 mm. The load is stored on standard EURO pallets with basic dimensions of 800 mm x 1200 mm. The height of the storage unit is 1200 mm. The maximum weight of the storage unit is 1000 daN.

The orientation of the entry-exit zones is defined so that the entry and exit are on the different sides at the same level. The racking structure is of the assembly-disassembly type. The connection between upright frames and horizontal beams is achieved via upright columns and beam end connectors.

The working aisle dimensions between each rack and the rack's height depend on the characteristics of the forklift trucks, lifting devices, dimensions of the external structure, and specific needs [8-10]

The comparative analysis will be carried out depending on the method of stacking the storage unit into the selective racks. Therefore, the design of the warehouse with transverse and longitudinal pallet stacking was considered.

3.1. Horizontal Racking Beams

In the first case, the adopted storage unit stacking method is transverse handling. To achieve a lightweight structure, a smaller number of storage units per pair of beams is preferred. A higher number of units per bay requires longer horizontal beams. However, a higher number of storage units also demands a greater load capacity for the horizontal beams, thereby requiring a stronger cross-section and a higher structural mass. Therefore, two cases will be considered when determining the horizontal beam length, with clearances within the limits of $A = 50 \text{ mm} \div 100 \text{ mm}$, according to [7,11].

- When a single storage unit is stacked crosswise on a pair of horizontal supports, the following applies:

$$L_{G1} = 2 \cdot A + B = 2 \cdot [50 \div 100] + 1200 = [1300 \div 1400] \text{ mm} . \quad (2)$$

For the first case of stacking, and according to [12], the standard beam length of $L_{G1} = 1300 \text{ mm}$ is adopted. Dimension A refers to the aforementioned clearance, while dimension B was previously represented by x in Figure 1.

- When two storage units are stacked crosswise on a pair of horizontal beams, then:

$$L_{G2} = 3 \cdot A + 2 \cdot B = 3 \cdot [50 \div 100] + 2 \cdot 1200 = [2550 \div 2700] \text{ mm} . \quad (3)$$

For the second stacking scenario, with a load capacity of 2000 daN, according to [12], standard beam length $L_{G2} = 2700 \text{ mm}$, a standard beam type with defined clearances between all elements of $A = 100 \text{ mm}$ was adopted.

In the case of transverse stacking, it was assumed that the optimal solution is the storage of two storage units in the form of two standard EURO pallets. The storage unit beam is marked as R120L (120 indicates the profile height, while L defines the thickness of the wall of the carrier, which is 1 mm).

In the second case, the adopted method of stacking will be longitudinal. Longitudinal stacking of one storage unit is not considered. In practice, this type of stacking is practically not applied, because it leads to a significant reduction in storage capacity, an increase in the number of racking structure components, and thus unnecessary costs. Two potential solutions will be considered when determining the length of the storage unit supports with clearances according to [7].

When two storage units are stacked longitudinally on a pair of horizontal supports, the following is valid:

$$L_{G1} = 3 \cdot A + 2 \cdot B = 3 \cdot [50 \div 100] + 2 \cdot 800 = [1750 \div 1900] \text{ mm} . \quad (4)$$

For the first case of stacking, and according to [12], the standard beam length of $L_{G1} = 1800$ mm is adopted.

When three storage units are stacked longitudinally on a pair of horizontal beams, then the following is valid:

$$L_{G2} = 4 \cdot A + 3 \cdot B = 4 \cdot [50 \div 100] + 3 \cdot 800 = [2600 \div 2800] \text{ mm} \quad (5)$$

For the second stacking scenario, according to [12], for the required load capacity of 3000 daN and the standard length $L_{G2} = 2700$ mm, a beam type designated as *R140L* is adopted. The designation 140 denotes the height of the profile, while *L* defines the thickness of the support wall, which is 1 mm. In this case, the three storage units will be placed on one support, with the clearance between the observed elements being slightly smaller than in the transverse stacking, and amounting to $A = 75$ mm. This stacking method will be further considered for comparative analysis, because it is assumed to be a more economical solution compared to the stacking of two storage units.

3.2. Upright Frame

It is necessary to determine the width of the upright frame, the height of the floor and the total height of the frame.

3.2.1. Width of the Upright Frame

The width of the frame is equal to the shortest dimension of the pallet at the base that enters the rack, i.e. 800 mm, in the case of transverse stacking. In the case of longitudinal stacking, the width of the frame is smaller than the dimension of the loaded pallet 1200 mm, i.e. 1100 mm.

3.2.2. Floor Height or Pitch

The floor height for both stacking scenarios is:

$$h_s = h + \Delta + h_n = 1200 + [75 \div 100] + 140 = [1415 \div 1440] \text{ mm} . \quad (6)$$

The resulting calculated value of the floor height must be divisible by the perforation pitch, so that a whole number is obtained as the quotient.

$$\frac{h_s}{p} = \frac{[1415 \div 1440]}{75} = [18.86 \div 19.02] \quad (7)$$

Since the integer value of the perforated holes was not obtained, two cases are considered:

- When the number of perforated holes $n_{p1} = 18$:

$$h_{s1} = n_{p1} \cdot p = 18 \cdot 75 = 1350 \text{ mm} \quad (8)$$

Based on the previously obtained value, the clearance Δ is:

$$\Delta = h_{s1} - h - h_n = 1350 - 1200 - 100 = 50 \text{ mm} \quad (9)$$

- When the number of perforated holes $n_{p2} = 19$:

$$h_{s2} = n_{p2} \cdot p = 19 \cdot 75 = 1425 \text{ mm} \quad (10)$$

In this case, the clearance Δ is:

$$\Delta = h_{s2} - h - h_n = 1425 - 1200 - 100 = 125 \text{ mm} \quad (11)$$

For the first case, with 18 perforated holes, the clearance between the beam and the storage unit is too small, and given the most commonly used transport and handling equipment in this storage system, such precision during stacking cannot be expected. Therefore, the second case is adopted, with 19 perforated holes and a calculated clearance of at least 125 mm, where the standard value of the floor pitch $h_s = 1500$ mm is adopted, according to [12].

3.2.3. Upright Frame Height

The total number of floors is determined as the quotient of the available height of the storage space and the adopted height of one floor:

$$n_s = \frac{H}{h_s} = \frac{7500}{1500} = 5 \quad (12)$$

Given that the first floor is on the ground floor, and the total number of floors according to expression (12) is obtained as an integer, the final number of floors will be:

$$n_n = n_s - 1 = 5 - 1 = 4 \quad (13)$$

Taking into account the height of the storage space, the total number of floors for both placement cases will be 4+1. The last floor is located at a height of 6000 mm, which further affects the height of the load lifting when choosing the material handling equipment.

3.2.4. Dimensioning of the Upright Frame

For a defined number of floors, two storage units per bay with transverse stacking, for a floor pitch of 1500 mm, the required frame load capacity is 8000 daN. Therefore, the column profile *S80M* is adopted, with a total frame load capacity $Q = 10300$ daN, based on data from [12]. The mass of the adopted profile per unit length is 4.23 kg/m. In the designation of the adopted vertical column profile, 80 denotes the height of the profile, while *M* defines the column wall thickness, which is 2 mm. Variable loads, in addition to the constant load determined by the own weight of the racking structure, in the form of stacked storage units on the horizontal supports for the case of transverse stacking, are shown in Figure 2 a).

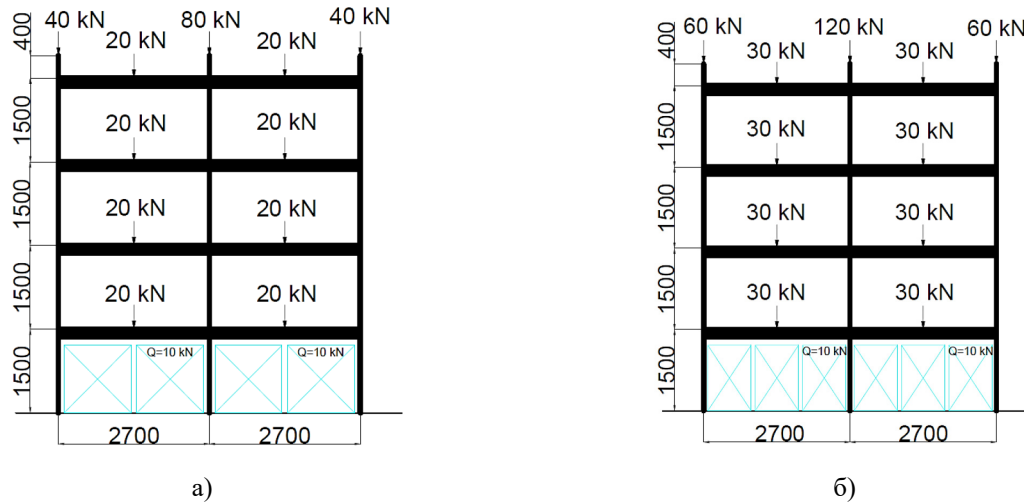


Figure 2: Illustration of the loads on vertical columns for the case of: a) transverse stacking of the two storage units, b) longitudinal stacking of the three storage units

According to the adopted number of floors and three storage units per bay in the case of longitudinal stacking, floor pitch of 1500 mm, the minimum load capacity of the frame is 12000 daN. Therefore, the column profile *S80MH* is adopted, with a maximum load capacity $Q=12800$ daN, based on data according to [12]. The mass of the adopted profile per unit length is 5.23 kg/m. In the designation of the adopted vertical column, 80 indicates the height of the profile, while *MH* defines the column wall thickness, which is 2.5 mm. The variable loads on the rack structure in the longitudinal stacking in the longitudinal direction, caused by the weight of the stored load, are shown in Figure 2 b).

It can be seen that the central upright is loaded twice as much as the edge uprights, because it accepts the load from the bays on both the left and right sides, which is the basis for its dimensioning.

According to the defined loads acting on the rack structure, it can be concluded that the load on the rack structure is greater in the case of longitudinal stacking than in the case of transverse stacking, by the weight of one storage unit per bay. This statement is also confirmed based on the adopted profiles of upright columns and transverse beams, because in the case of longitudinal stacking, the profiles with larger dimensions and load capacity were adopted compared to transverse stacking.

3.3. Cross Beam

A cross beam with dimensions of 810 mm x 80 mm x 45 mm x 1.25 mm is adopted, with the load capacity of a pair of cross beams being 1020 kg. The mass of the beam is 1.66 kg/piece. In the case of longitudinal stacking, the presence of cross beams is not required.

3.4. Transport and Handling Device

A very narrow aisle truck STILL NXV 16 with swivel traverse fork is used as a transport and handling device, which has a flexible range of applications for different loads and warehouse conditions. Its load capacity is 1500 kg, the maximum lift height is 6350 mm, and the working aisle width is 1662 mm.

3.5. Selecting the Optimal Solution

Taking into account the included design conditions, as well as the selection of racking construction elements, the racks are arranged in the transverse direction, i.e. along the shorter side of the storage space due to the orientation of the entry-exit zones. The operational passages between the racks are defined by the characteristics of the transport and handling equipment.

The width of the space intended for movement or transport, which does not allow direct access to the unit load, is 2200 mm for both racking configurations. In the case of transverse stacking, the racking arrangement is designed as a total of 20 double-row and 4 single-row racks, according to Table 1. Two storage units are stacked in one bay, with a total of 5 floors including the "floor" located on the ground floor. Figure 3 illustrates the optimal rack layout in the designated warehouse space, which is served by a racking forklift, with the stacking being transverse.

Table 1: Warehouse capacity with transverse pallet stacking

Rack designation	Rack type	Length, mm	Width, mm	Number of identical rows, pcs	Row capacity, pcs	Total rack capacity, pcs
P1	single-deep	16790	800	2	60	120
P2	double-deep	16790	1685	8	120	960
P1	single-deep	8430	800	1	30	30
P2	double-deep	8430	1685	8	60	480
P1	single-deep	5650	800	1	20	20
P2	double-deep	5650	1685	3	40	120
P2	double-deep	2865	1685	1	20	20
Total warehouse capacity, pcs						1750

For the case of longitudinal stacking, the rack layout is designed as a total of 16 double-row and 4 single-row racks, more precisely defined in Table 2. In relation to transverse stacking, 3 storage units are stored in each rack bay in one section, with a total of 5 floors including the 'floor located on the ground floor. Figure 4 illustrates the optimal rack layout in the intended storage space, which is served by a rack forklift, where the storage unit is stacked longitudinally.

Table 2: Warehouse capacity with longitudinal pallet stacking

Rack designation	Rack type	Length, mm	Width, mm	Number of identical rows, pcs	Row capacity, pcs	Total rack capacity, pcs
P1	single-deep	16790	1200	2	90	180
P2	double-deep	16790	2500	6	180	1080
P1	single-deep	8430	1200	2	45	90
P2	double-deep	8430	2500	6	90	540
P2	double-deep	5650	2500	3	60	180
P2	double-deep	2865	2500	1	30	30
Total warehouse capacity, pcs						2100

The comparative analysis of the rack layout refers to both the achieved capacity and the weight of the rack structure. The total weight of all elements of the rack support structure with transverse stacking is 37088 kg, while with longitudinal stacking it is 28683 kg. Based on the given data, it can be concluded that, the optimal solution in terms of the weight of the observed rack settings is with longitudinal stacking.

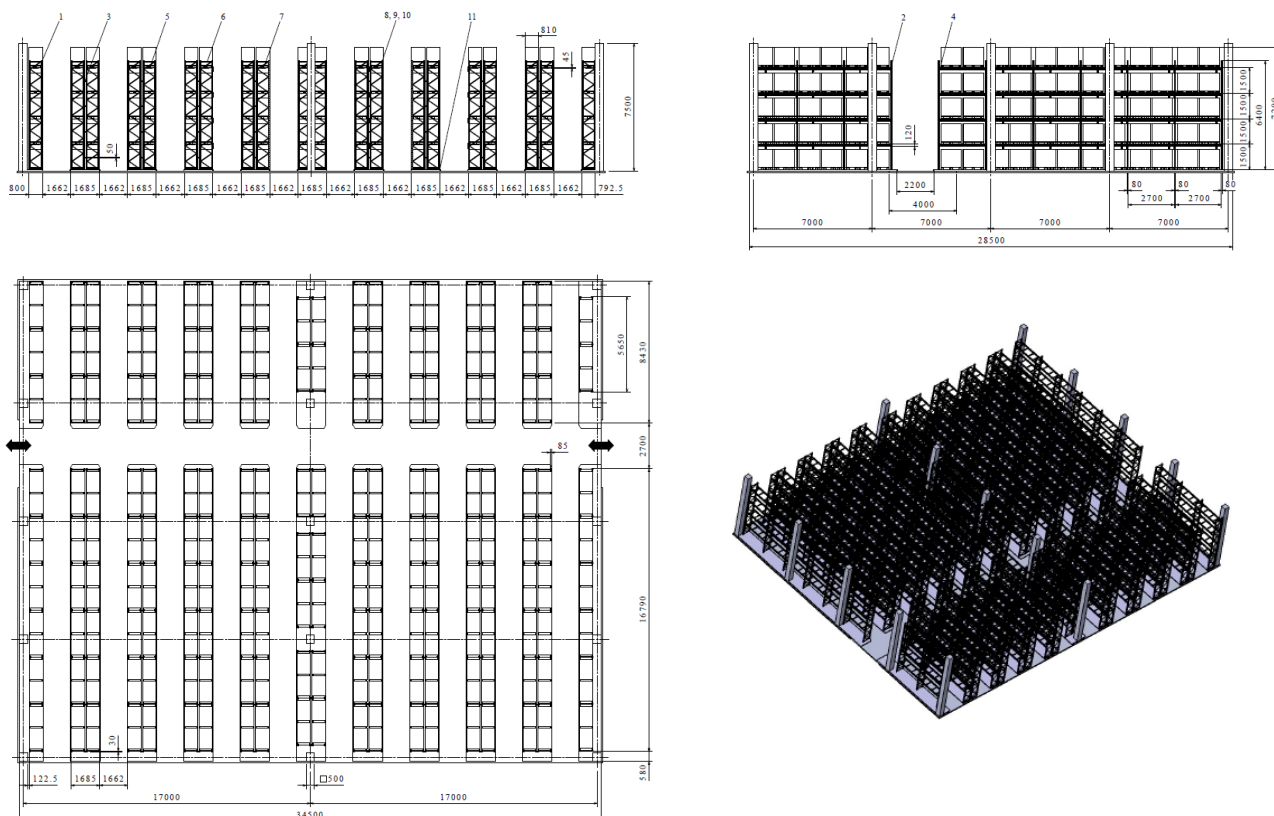


Figure 3: Warehouse layout with transverse pallet stacking

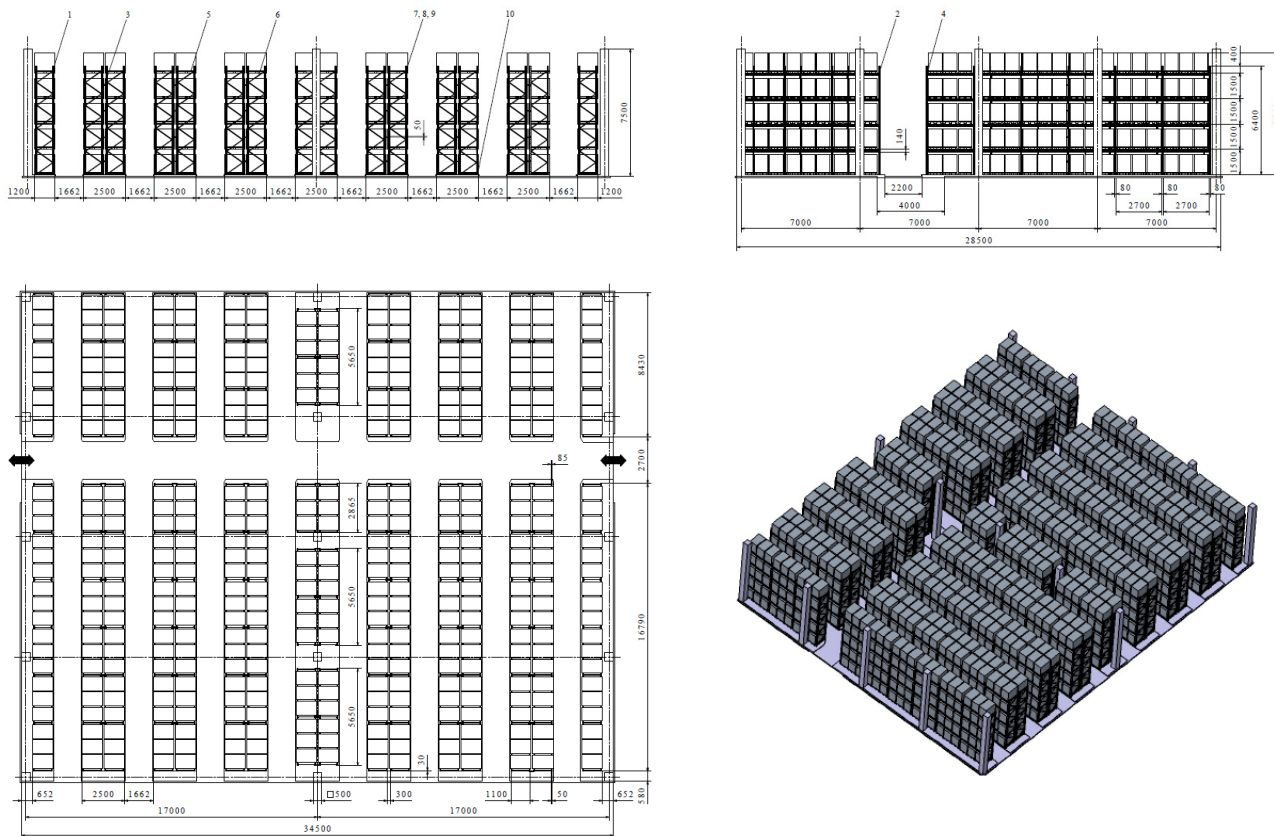


Figure 4: Warehouse layout with longitudinal pallet stacking

The key difference between longitudinal and transverse stacking is reflected in the position of the stacked storage unit, as well as in the number of units stored within a single bay. Also, compared to longitudinal stacking, transverse stacking requires the presence of cross beams supports for the storage units, which complicates and increases the cost of the rack structure to a certain extent.

The aisle width is the same for both stacking options, because the same material handling equipment is used to serve the storage space.

Considering the dimensions of the racks, the frame width is greater for longitudinal stacking. Despite the fact that the racks for transverse stacking are more compact in terms of construction, the greater storage space capacity, with the smaller number of racks, is achieved for longitudinal stacking by 20%.

Considering the number of rack elements, a smaller number of elements is certainly used in the case of longitudinal stacking, given that there are fewer rows of racks.

Given the achieved higher storage capacity and lower own weight of the rack structure elements, the rack layout with longitudinal stacking of storage units is adopted as an optimal, more economical solution.

4. CONCLUSION

Selective pallets racks, also known as adjustable or conventional racks, are the most widespread due to their economy, simplicity and efficiency. This type of rack is designed as a skeletal structure with a steel frame intended for the storage of usually palletized goods in a conventional manner.

The primary task of any rack warehouse is to maximize the available space and enable safe storage of goods. Pallet racks should be designed in such a way that they adapt to the type and dimensions of pallets with a unit load and can carry a certain weight, taking into account storage at multiple levels. Great attention should be paid to the selection of racks that best meet the requirements in terms of easy access to goods and efficient use of warehouse space. The rack, as the foundation of a warehouse, is crucial to enabling optimal and efficient flow of goods, because it is precisely this efficiency that depends on the use of an adequate racking system.

Pallet rack systems allow material handling equipment to smoothly access the storage units. Today, racks are most often designed as modular, which means they can be adapted and rearranged, which is primarily reflected in the advantage of their application. Selective pallet racks are an ideal choice for warehouses that prioritize the storage unit that is first placed in the rack, first taken out, namely FIFO. This system ensures that the earliest received storage units are retrieved first, promoting efficient stock rotation and minimizing the risk of product expiration.

Also, the correct selection of forklift truck characteristics is important for the efficient use of space within the layout of selective pallet racks.

According to the achieved capacity, the weight of the rack structure and the number of rack elements, the installation of racks with longitudinal stacking is more economical. The disadvantage of transverse stacking compared to longitudinal stacking is also reflected in the use of cross beams, which further complicate and increase the cost of the structure.

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