The 11th International Congress
Motor Vehicles & Motors 2026
Kragujevac, Serbia
October 8th - 9th, 2026

Motor Vehicles & Motors

MVM2026-076
https://doi.org/10.24874/CMVM2026.076
Original scientific paper

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WAREHOUSE SYSTEMS IN THE AUTOMOTIVE INDUSTRY: A COMPARATIVE STUDY OF STORAGE SYSTEMS, HANDLING EQUIPMENT AND SAFETY CLEARANCE

ABSTRACT: The paper presents a comparative analysis of the impact of storage methods, handling equipment, and safety clearance on the selection of warehouse systems in the automotive industry. Pallet racking systems are straightforward, efficient, and widely utilized for storing goods on pallets. They offer immediate and unhindered access to each pallet at any given moment. After defining the storage unit, the beams and upright frames were sized accordingly. Suitable handling and retrieval equipment was then selected. The layout of the racks within the warehouse was designed based on standard storage system principles. To ensure the proper design, manufacturing, assembly, and operation of warehouses, it is essential to accurately define the tolerances, deformations, and clearances of the system elements. Finally, proper structural components were chosen, the total warehouse capacity was determined, and a comparative analysis was done to evaluate both transverse and longitudinal pallet placement for selective racking.

KEYWORDS: warehouse, material handling equipment, storage and retrieval machines

SKLADIŠNI SISTEMI U AUTOMOBILSKOJ INDUSTRIJI: UPOREDNA ANALIZA SISTEMA SKLADIŠTENJA, OPREME ZA RUKOVANJE I SIGURNOSNIH ZAZORA

REZIME: U radu je prikazana uporedna analiza uticaja načina skladištenja, opreme za rukovanje robom i sigurnosnih zazora na izbor skladišnih sistema u automobilskoj industriji. Paletni regalni sistemi su jednostavni, efikasni i široko rasprostranjeni za skladištenje paletizovane robe. Oni omogućavaju trenutan i nesmetan pristup svakoj paleti u bilo kom trenutku. Nakon definisanja skladišne jedinice, izvršeno je odgovarajuće dimenzionisanje greda i stubova regala. Zatim je izabrana odgovarajuća oprema za rukovanje i preuzimanje robe. Raspored regala u

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skladištu je projektovan na osnovu standardnih principa skladišnih sistema. Da bi se obezbedilo pravilno projektovanje, izrada, montaža i rad skladišta, neophodno je precizno definisati tolerancije, deformacije i zazore elemenata sistema. Na kraju, izabrane su odgovarajuće strukturne komponente, određen je ukupan kapacitet skladišta i urađena je uporedna analiza kako bi se procenilo i poprečno i uzdužno postavljanje paleta kod selektivnih regala.

KLJUČNE REČI: skladište, oprema za manipulaciju materijalom, regalne dizalice

INTRODUCTION

The automotive industry operates on a massive scale. It requires high speed, accuracy, and efficiency. Every car is made of thousands of parts. Managing these parts is a complex job. Intralogistics, the movement of goods within a warehouse, is the backbone of this industry. Automotive supply chains rely heavily on Just-In-Time and Just-In-Sequence manufacturing. This means parts must arrive at the assembly line exactly when they are needed. Because of this, picking the right warehouse systems, handling equipment, and safety rules is important for the smooth operation of automotive factories.

The primary objective of modern storage systems is the efficient storage and rapid distribution of large quantities of goods within a designated space. A standard pallet racking system comprises three core components: the racks, the pallets, and the handling equipment or forklifts. Each component is selected based on the specific materials stored, operational demands, positioning systems, and the chosen management model (Vujanac & Miloradović, 2023). Generally, the spatial frame structure of a pallet rack consists of upright frames and horizontal beams. These are typically manufactured from thin-walled, cold-formed profiles to create the final rack configuration.

Selective pallet racking remains the most widely used solution, accommodating a diverse range of unit loads while providing direct access to every pallet (Miloradović & Vujanac, 2025). To upgrade standard layouts, double-deep pallet racking can be implemented, allowing each shelf to hold two rows of pallets instead of one. Alternatively, mobile pallet racking maximizes space utilization by eliminating multiple static aisles. Other highly efficient solutions include drive-in and drive-through racking systems. Additionally, pallet flow systems utilize gravity, wheels, or rollers to dynamically transfer and store pallets. The basic components of any pallet racking system include vertical frames, horizontal beams, baseplates with anchors, and row spacers. Applying European standards and regulations to the determined structural properties allows for a comprehensive analysis of the rack configuration and its individual components (EN 1993, 2005; FEM 10.2.02, 2000; EN 15512:2020+A1:2022, 2022).

Depending on the requirements placed on rack warehouses, a large number of different types of rack configurations have been developed. These requirements relate to storage capacity, storage methods, retrieval methods, the characteristics of the stored material, and the handling equipment used. Some of the characteristic pallet rack configurations are shown in Figure 1.

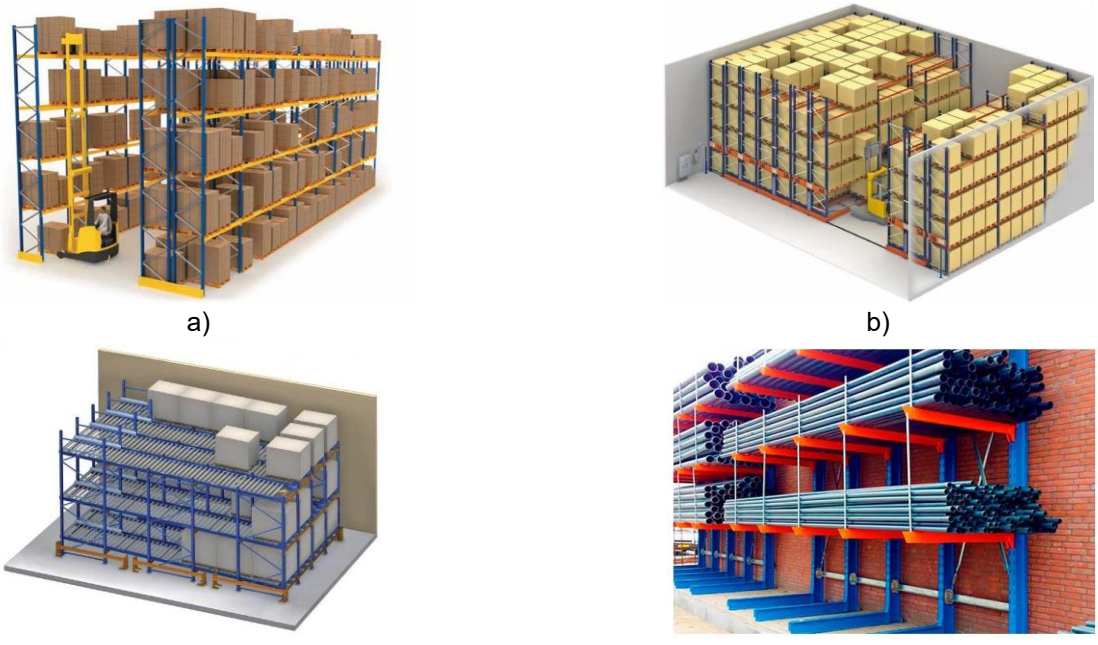


Figure 1 Different types of pallet racks: a) self-supporting racks, b) mobile racks, c) pallet flow racks, d) cantilever racks

WAREHOUSE SYSTEM

The selection of racking structural components primarily depends on the available storage space and the characteristics of the storage unit.

Configuration of Pallet Racking

The spatial frame of a pallet racking system consists of side frames and horizontal beams, which are typically made from thin-walled, cold-formed steel profiles. Stability across the aisles is provided by a system of horizontal and vertical bracing. To ensure down-aisle stability, specialized beam-to-column connectors with features like tabs, studs, or hooks are either welded to the beams or integrated directly into them. These connectors lock into the column perforations, creating a rigid connection that keeps the entire structure stable along the corridor (Vujanac et al., 2020).

A typical selective pallet rack configuration is shown in Figure 2.

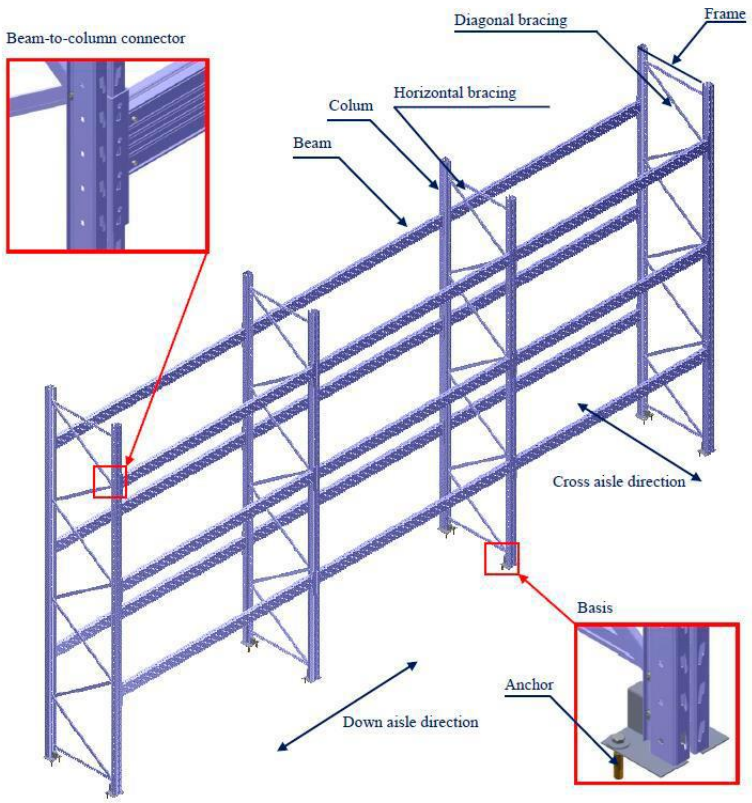


Figure 2 Typical configuration of a pallet rack structure

Storage and retrieval equipment

Forklifts commonly operate within rack warehouses, serving as a highly advanced type of material handling equipment that can actively retrieve, position, and vertically stack loads

To fulfil the investor's primary objective of maximizing storage capacity and volume within the available space, designers must thoroughly understand the capabilities of storage and retrieval equipment, the selection of which depends on:

- storage unit,
- frequency of the storage units entering into and exiting from the warehouse,
- orientation of the entrance - exit zones,
- the number of the storage units within the high-bay warehouse (storage capacity),
- warehouse connections with external transport.

In this manner, the primary advantage of such warehouses - maximizing space utilization and enhancing operational efficiency - will be fully realized.

Safety clearance

Adjustable pallet rack system can be installed in two configurations: wide aisle or narrow aisle pallet racking. In both solutions some protective components of pallet racking (rack protectors) are necessary even they are not mandatory equipment. Protective components for pallet racking have been designed, manufactured and applied in accordance with current EN standards and FEM regulations:

- Structural design in accordance with EN 15512. Steel static storage systems - Adjustable pallet racking systems - Principles for structural design, (EN 15512, 2009).
- Parameters for application in accordance EN 15620. Steel static storage systems - Adjustable pallet racking - Tolerances, deformation and clearances, (EN 15620, 2008).
- In terms of basic applications and installation locations of column and frame protectors EN 15629. Steel static storage systems - Specification of storage equipment, (EN 15629, 2008).
- In terms of dimensions, construction and required resistance to damage FEM 10.2.16. The Design and Use of Rack Protection for Adjustable Pallet Racking - Upright and Frame Protection, (FEM 10.2.16, 2017).

Correct protection of pallet rack systems against material handling equipment impacts is essential for preventing structural damage to the racking system. Upright protectors are designed as corner or internal protectors within the aisles. The frame guard shown in Figure 3 protects the corner and rear uprights with frame bracing. The allowable clearance within the rack bay is determined by the EN 15620 standard. The clearance between the edge of the upright protector and the side of the upright is also defined (≤40 mm), as shown in Figure 4 a). If the specified distance is greater, then the total clearance is additionally increased in accordance with the recommendations in Figure 4 b). Also, protectors must be designed to withstand and absorb the appropriate impact energy in accordance with standards.

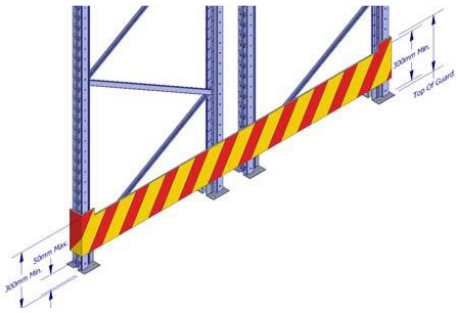


Figure 3 Frame protector

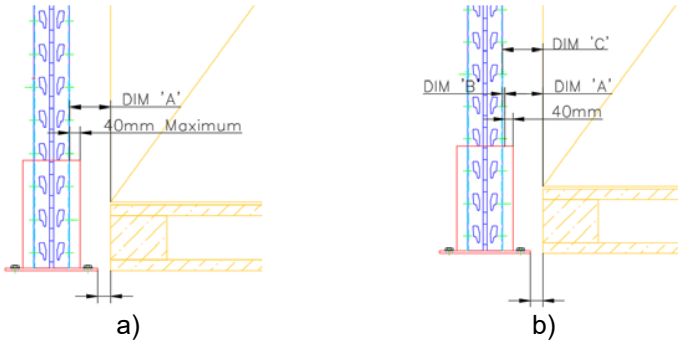


Figure 4 The minimum distance from the upright to the protector

A special place in storage technology belongs to the so-called narrow aisle racks, which are characterized by the corridor width that is sufficient only for the straight-line passage of the storage and retrieval machines (S/R) carrying the unit load, with very small operational clearances, (FEM 10.3.01., 1997; FEM 9.101., 1997).

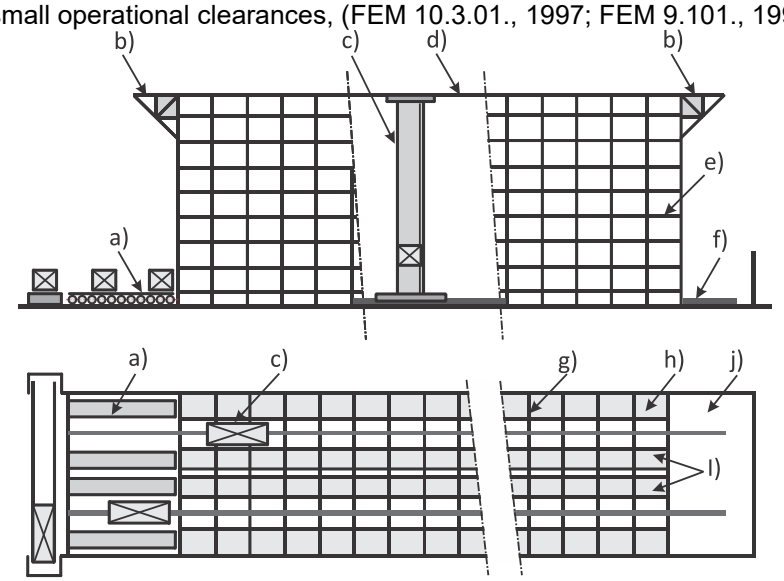


Figure 5 Narrow aisle racks: a) conveyors, b) S/R machines run-out, c) S/R machines, d) upper guide rail, e) beam, f) bottom rail, g) portal tie beam, h) single entry run, i) double entry run, j) maintenance area

Clearances exist to prevent collisions within the storage systems. Actually, they are required nominal distances between fixed and moving parts, taking into account all individual tolerances and deformations. The entry clearances are the clearances between the load make-up accessory and the load handling device. The rack compartment clearances exist between the unit load and the rack structure, while the aisle clearances are the clearances between

the outer most edge of the S/R machine and the outermost edge of the rack structure or the load, as well as the clearances at the rear of the stored load.

The calculation of clearances takes into account the following influencing factors: floor slab, floor rail, upper guide rail, unit load, S/R machines and rack structure.

The fork entry clearances that exist between the load handling device and the load make-up accessory are shown in Figure 6:

- X_1 - on the side of the load handling device which is the furthest from the mast,
- X_2 - on the side of the load handling device which is the closest to the mast,
- Y_1 - between the load handling device and the load supporting beam and
- Y_2 - between the load handling device and the load make-up accessory.

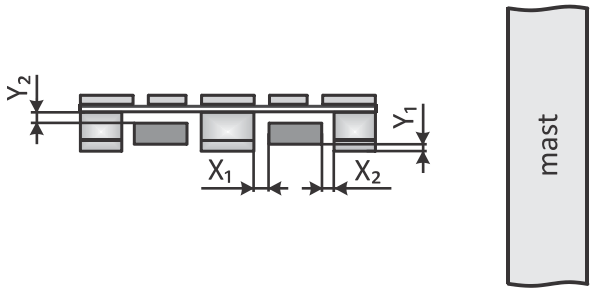


Figure 6 Fork entry clearances

The rack compartment clearances are the minimum distances shown in Figure 7:

- $X_{3.1}$ - between the unit loads and the uprights on the side which is the furthest from the mast.
- $X_{3.2}$ - between the unit loads and the uprights on the side which is the closest to the mast,
- X_4 - between the individual unit loads,
- Y_3 - between the top of the unit load and the rack structure and/or other obstructions,
- Y_4 - between the underside of the raised unit load and the top of the lower support beam,
- Y_5 - between the underside of the higher support beam and the top of the raised unit load.

While overly small clearances pose a risk to operational safety and can disrupt warehouse handling operations, excessively large clearances result in wasted storage space.

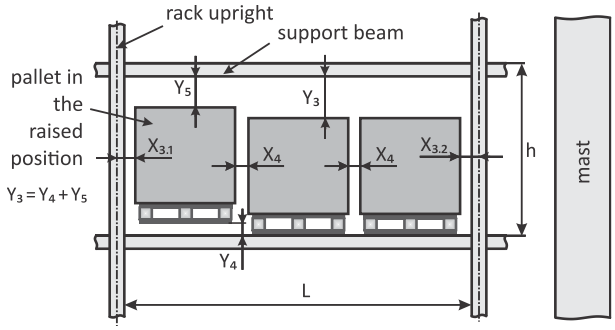


Figure 7 Rack compartment clearances

The aisle clearances are the minimum distances shown in Figure 8:

- $Z_{1.1}$ - between the unit load and any obstruction on the building side (e.g. building structure, rainfall pipe).
- $Z_{1.2}$ - between the unit load and the rack structure inner racks,
- $Z_{2.1}$ - between the outermost point of the lifting carriage or the unit load on the lifting carriage and the nominal position of the stored load or the rack structure with a protruding load in the stored position on the outer rack side,
- $Z_{2.2}$ - the same, on the inner rack side,
- $Z_{3.1}$ – between fixed obstructions on the S/R machine (e. g. lifting mechanism or platform) and the stored load or the rack structure. Outer rack side.
- $Z_{3.2}$ – the same, on the inner rack side.

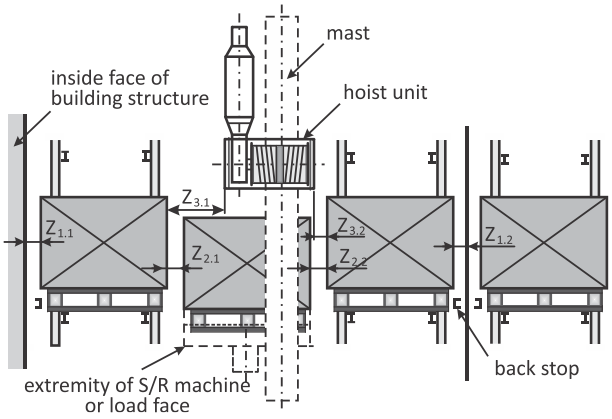


Figure 8 Aisle clearances

COMPARATIVE ANALYSIS

The proposed warehouse layout features a length of 34,500 mm, a width of 28,500 mm, and a height of 7,500 mm. Standard EURO pallets (800 mm x 1,200 mm) serve as the storage medium, with each unit measuring 1,200 mm in height and weighing up to 1,000 daN.

The facility is configured with separate entry and exit points located on opposite sides at the same elevation. For the storage framework, a modular, boltless racking system is utilized, where beam end connectors join the horizontal beams directly to the upright columns.

The comparative analysis focuses on how storage units are deposited into the selective racks. Consequently, the warehouse design evaluates both transverse and longitudinal pallet placement (Figures 9 and 10). For both stacking scenarios, specific parameters were established: standard beam length, upright frame height, and floor height clearance.

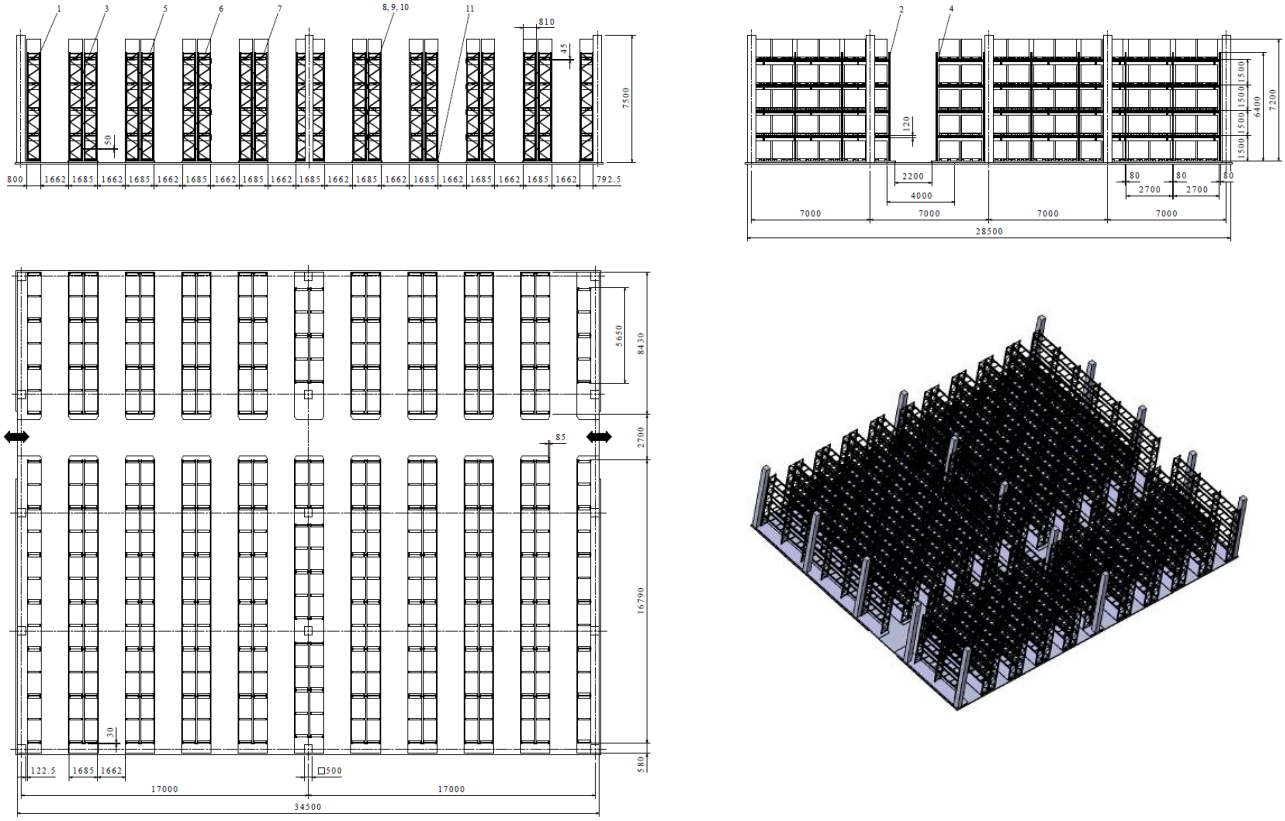


Figure 9 Warehouse layout with transverse pallet stacking

The material handling operations rely on a STILL NXV 16 very narrow aisle truck equipped with a swivel traverse fork. This vehicle offers highly flexible application across diverse loads and warehouse layouts, featuring a 1,500 kg lifting capacity, a 6,350 mm maximum lift height, and requiring a working aisle width of 1,662 mm.

The comparative analysis will be conducted based on the method of stacking storage units into the selective racks. Consequently, warehouse designs featuring both transverse and longitudinal pallet stacking were evaluated.

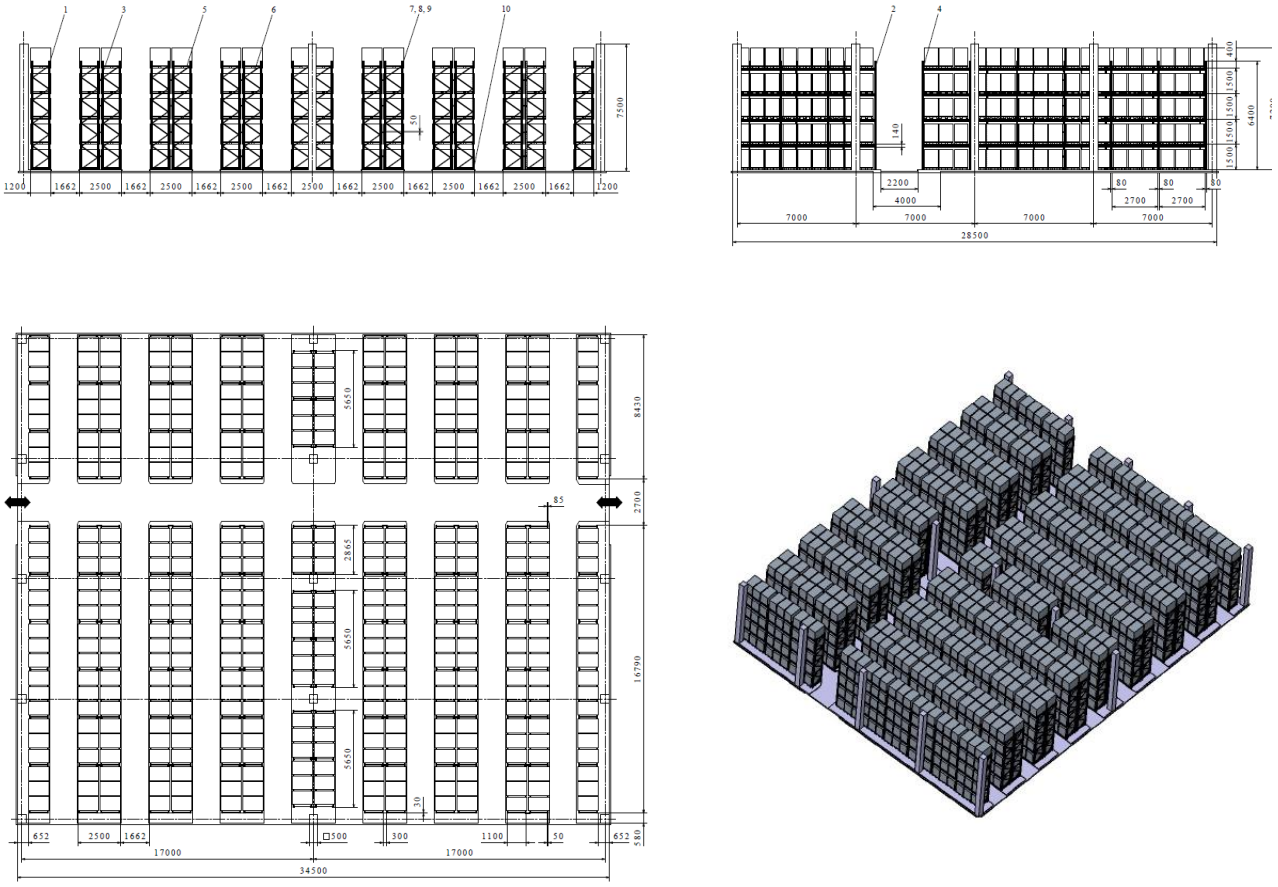


Figure 10 Warehouse layout with longitudinal pallet stacking

Based on the defined loads acting on the racking structure, it can be concluded that the structural load is greater in longitudinal stacking than in transverse stacking, specifically by the weight of one storage unit per bay. This assertion is further confirmed by the selected profiles for the upright frames and beams; the longitudinal configuration requires profiles with larger dimensions and higher load capacities than the transverse arrangement.

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 37,088 kg, while with longitudinal stacking it is 28,683 kg.

Based on the data provided, it can be concluded that the optimal solution regarding the weight of the analysed racking configurations is the one with longitudinal stacking.

Considering the dimensions of the racks, the frame width is greater for longitudinal stacking. Although the racks for transverse stacking are more structurally compact, the longitudinal configuration achieves a 20% higher storage capacity while utilizing fewer racks.

Regarding the number of components, the longitudinal stacking configuration utilizes significantly fewer elements due to the lower number of racking rows.

CONCLUSIONS

Pallet rack damage can be extremely costly and dangerous. To prevent the collapse of the rack structure and the load itself, minimizing the risk of damage to pallet racking is one of the major challenges facing today's automotive warehousing industry.

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: 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.

Based on the achieved capacity, structural weight, and component count, the longitudinal stacking configuration proves to be more economical. Furthermore, the disadvantage of transverse stacking lies in the requirement for additional cross-beams, which increases both structural complexity and manufacturing costs.

ACKNOWLEDGMENTS

This research was supported by the Ministry of science, technological development and innovation of the Republic of Serbia, contract number 451-03-34/2026-03/200107.

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