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Optimization of Unit-Load Formation and Facility Design: A Comprehensive Guide to Pallet Selection and Inventory Logistics

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ABSTRACT

Effective facility design and unit-load formation are critical factors in optimizing modern warehouse operations and minimizing supply chain costs. While various handling equipment options exist, pallets serve as the primary structural foundation for maximizing storage and transport efficiency. This study outlines a systematic approach to equipment selection and dimension optimization within a large-scale industrial warehouse design. It evaluates pallet material performance across wood, plastic, and metal alternatives. To overcome the challenges of standardizing handling procedures, two distinct optimization workflows—Linear Programming (LP) and Space Utilization Efficiency (SUE)—are examined to identify the ideal footprint for uniform racking configurations. Comprehensive inventory modeling is then applied to calculate total pallet capacity constraints under specified load weights, height boundaries, and stack ability limits.

Based on structural and economic parameters, premium wooden pallets measuring 1000mm X 900mm X 150mm were selected, achieving an optimal spatial efficiency of up to 94.4% for core inventory components. To fully support the facility's inventory demands across nine distinct material classes, the total fleet requirement was mathematically determined. The logistics analysis indicates that the warehouse requires a total infrastructure capacity of 185,663 standardized pallets, comprised of 181,376 units for primary cycle and safety stock alongside 4,287 units for dedicated buffer operations. Implementing this uniform pallet standard minimizes floor space loss, simplifies shelf design, and establishes a highly streamlined material handling workflow.

Keywords: Facility Design, Unit-Load Formation, Space Utilization Efficiency (SUE), Linear Programming, Warehouse Logistics, Inventory Standardization.

INTRODUCTION

In modern warehouse and facility design, selecting the right unit-load formation equipment is vital to minimizing costs and boosting operational speed. While options like skids, slip-sheets, and pallet boxes are widely used, pallets remain the industry's primary choice. [1] analyzes the selection, material classification, and mathematical dimensional optimization of pallets for large-scale inventory management. Research by [2] addresses the optimization of Stacked Pallet Load Units (SPLUs) comprised of individual, elementary Pallet Load Units (PLUs). In logistical operations, elementary PLUs frequently present heights and gross weights that fall well below maximum allowable limits. To maximize efficiency, logistics planners seek mechanisms to stack these smaller units, thereby minimizing the physical footprint required on vehicle load beds or within warehouse racking slots. [3] study analyzes the unique challenges that Omni channel distribution imposes on modern warehouse operations. First, it identifies a comprehensive inventory of these difficulties, organizing them into four distinct categories. Building on this framework, the research investigates how each challenge impacts specific warehouse zones and core management variables. Ultimately, this analysis aims to map out the broader effects of the Omni channel landscape on warehouse environments while proposing actionable countermeasures to minimize operational complexity.

This stacking process operates under several strict parameters:

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- **Compliance:** The final consolidated SPLUs must strictly adhere to legally permissible weight and height thresholds.
- **Invariance:** The elementary PLUs are pre-assembled based on unique customer specifications; their internal content cannot be altered or broken down.
- **Composition:** Individual PLUs may consist of either homogeneous or mixed product lines, provided the customer has consented to stacked delivery.

To resolve similar logistical bottlenecks, [4] examined a comprehensive array of practical warehouse constraints, including vertical support mechanics, structural load-bearing limits, planogram sequencing, and strict weight distribution boundaries. Their numerical evaluations demonstrated that optimized computational approaches can yield high-quality structural configurations for industrial-scale operations within minimal timeframes.

Similarly, recent literature emphasizes accelerating computational speeds for large datasets.[5] focused on engineering an approximate Bin Packing Problem (BPP) algorithm tailored for large-scale operations, introducing a modified Squirrel Search Algorithm (SSA) to resolve one-dimensional bin packing challenges. When evaluated against difficult test sets containing up to 200 distinct items, the SSA model outperformed competitive approximate heuristics, such as Particle Swarm Optimization (PSO), African Buffalo Optimization (ABO), and the Crow Search Algorithm (CSA).

In parallel, alternative mathematical formulations have been introduced to organize non-uniform, cubical items within finite loading zones. One model incorporates variables such as the varying dimensions, masses, structural tolerances, and vertical axis rotations of individual packaging units. A foundational, analogous framework was pioneered by [6] who modeled the placement of cuboidal packaging units into identical cubic containers using exact coordinate mapping (anchored at the lower-left-hand corner) to define precise spatial positioning.

Structural Role of Pallets in Logistics

Complementing these mathematical frameworks is the physical utility of the transport infrastructure itself. Investigated by [7] to improve materials and structural integrity, the pallet serves as a foundational flat structure that stabilizes cargo during mechanical transit via forklifts, pallet jacks, or front loaders. Acting as the structural foundation of a consolidated unit load, pallets are central to warehouse throughput and storage density. During preparation, goods or storage containers are systematically arranged on the surface and anchored using industrial strapping or stretch wrap to ensure safety throughout the supply chain.

A sequential, two-step approach to pallet assembly and truck loading was explored by [8]. Their framework treats pallet configuration as the primary stage and truck positioning as the secondary stage. To ensure practical applicability, the authors factored in total weight capacities, distribution limitations within the container, and maximum axle loads, alongside allowing vertical pallet stacking. This optimization problem was tackled using a GRASP algorithm, with computational experiments focusing on instance variety, vehicle numbers, and execution speed. [9] conducted a comprehensive evaluation focusing on the structural performance of hardwoods within traditional pallet designs. However, a primary limitation of the PDS software is its exclusive focus on wooden substrates, as it fails to account for alternative or composite materials increasingly used in modern material handling.

MATERIAL AND METHODS

A pallet acts as a flat transport structure that keeps goods stable while they are being lifted by mechanical devices like forklifts, pallet jacks, or front loaders. Serving as the structural backbone of a unit load, pallets drive warehouse handling and storage efficiencies. Goods or containers are typically arranged on top, secured with strapping or stretch wrap, and prepped for shipment.

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The Operational Pros and Cons of Palletization

Advantages:

- Boosts employee productivity.
- Reduces overall headcount requirements.
- Speeds up vehicle turnaround times, requiring fewer dock positions.
- Lowers workplace injuries.

Disadvantages:

- Requires designated warehouse space for storing empty units.
- Adds procurement and maintenance expenses.
- Contributes additional dead weight to delivery vehicles.

To maximize efficiency, standardizing warehouse operations across as few pallet dimensions as possible is highly recommended.

Pallet Classifications and Materials

Pallets are categorized by three primary criteria:

- **Use Category:** Multiple use vs. limited use.
- **Basic Construction Style:** Single face, double-face non-reversible, and double-face reversible.
- **Entry Type:** Determines equipment accessibility (2-way, partial 4-way, or full 4-way entry).

Material Comparison: Wood vs. Plastic vs. Metal

The table below breaks down the strategic pros and cons of the three primary pallet material choices:

Material	Key Advantages	Major Disadvantages
Wood	Cheap; recyclable/renewable; high friction; easily repaired.	Risk of pests/diseases (requires international treatment); prone to mold/moisture; hard to clean; splinters.
Plastic	Easy to sanitize; odor-resistant; long lifespan; lightweight; RFID tracking compatible; durable.	High initial cost; difficult to prototype; low friction; low stiffness; lacks easy repair options; variable fire ratings.
Metal	Exceptional strength and stiffness; bug-free; no splinters; moisture-resistant.	Very expensive initial price; heavy; low surface friction; carbon steel is prone to rusting.

Most standard pallets can securely support a structural load of up to **1,500 kg**. For a project warehouse handling loads up to this threshold, wooden pallets are chosen for their excellent balance of strength, cost efficiency, high availability, and ease of use.

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Selected Pallet Specifications

- **Dimensions:** 1000 mm × 900 mm × 150 mm
- **Material:** Knot-free premium wood with flathead threaded screw nails
- **Safety Features:** No protruding nails or warped boards; bottom edge boards are chamfered to allow clean entry for pallet truck forks.

RESULTS AND DISCUSSION

Pallet Dimension Optimization Techniques

Selecting an optimal standard dimension's matrix requires mathematical precision. Warehouse planners rely on two primary methodologies: Linear Programming (LP) and Space Utilization Efficiency (SUE).

Method I: Linear Programming (LP) Technique

Linear Programming is an operations research tool that optimizes resources to minimize procurement costs or maximize space utilization. To solve for the ideal pallet distribution across distinct inventory items, the optimization problem is formulated mathematically:

Minimize $Z = 45x_1 + 40x_2 + 35x_3 + 30x_4$

Subject to structural handling constraints:

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \leq 80{,}800$$

$$2x_1 + 2x_2 + 2x_3 + 2x_4 + 2x_5 + 2x_6 \leq 95{,}950$$

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \leq 70{,}700$$

$$6x_1 + 6x_2 + 6x_3 + 6x_4 + 6x_5 + 6x_6 \leq 108{,}500$$

And $x_1, x_2, x_3, x_4, x_5, x_6 \geq 0$

Where x_1 through x_6 represent various ISO standard pallet footprint metrics. This system can be solved definitively using the Simplex method.

Method II: Space Utilization Efficiency (SUE) Technique

The SUE methodology selects standard dimensions by minimizing wasted space. The foundational calculation is:

$$\frac{Unused\ space\ left\ by\ the\ element}{Standard\ pallet\ area}$$

Using computational analysis in MS Excel across multiple operational packages (including central stations, pumps, containers, and electric motors), efficiency tables reveal that a standardized **900 mm × 1000 mm** pallet achieves up to **94.4% spatial efficiency** for primary components. Since standardizing warehouse racking requires uniform dimensions, this footprint is selected because it handles the capacities of larger alternatives while saving floor space.

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Inventory Logistics and Total Pallet Calculations

To determine the final fleet requirements, planners calculate total pallet needs across two primary stock groupings: **Cycle & Safety Stocks** and **Buffer Stocks**.

The basic forecasting formula applied per inventory asset is:

$$No.of\ pallet\ required = \frac{inventory\ level}{No.of\ pieces/pallet}$$

1. Cycle and Safety Stock Calculations

Applying constraints based on physical package traits, maximum stack weights (1500 kg limit), and unit height boundaries (1000 mm maximum unit load height), total requirements are calculated per element:

- **Central Station:** Cannot be piled; 1 piece per pallet.

  Total stock: 82,400. Pallets required: 82,400.

- **Container:** Cannot be safely stacked vertically due to height limits; 2 pieces fit the footprint. Total stock: 107,100. Pallets required: 53,550.

- **Base:** 50 mm height allows 20 layers stacked vertically.

  Total stock: 87,550. Pallets required: 4,378.

- **Hydraulic Pump:** Cannot stack vertically; 4 items fit the surface area.

  Total stock: 92,700. Pallets required: 23,175.

- **Electric Motor:** Cannot stack; 9 items fit the surface.

  Total stock: 77,250. Pallets required: 8,584.

- **External Structure:** Stacks 2 layers high with 8 items per surface layer (16 total per pallet).

  Total stock: 82,400. Pallets required: 5,150.

- **Electric Card:** Stacks 5 layers high with 15 boxes per layer (75 per pallet).

  Total boxes: 114,620. Pallets required: 1,529.

- **Small Mechanical Units:** Weight/height limits allow 8 stacked layers with 60 boxes per layer (480 total per pallet). Total boxes: 663,080. Pallets required: 1,382.

- **Small Electrical Units:** Stacks 16 layers high safely underweight caps with 180 boxes per layer (2,880 total per pallet). Total boxes: 353,475. Pallets required: 1,228.

Cycle & Safety Stock Summary:

- **Total Units Handled:** 70,177,100 pieces

- **Total Primary Fleet Pallets:** 181,376 units

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2. Buffer Stock Calculations

Accounting for an operational buffer window based on daily active labor cycles (e.g., a 4-hour working run within a standard 15-hour day yields a **0.2667 buffer variable**), the separate backup buffer fleet is quantified:

- **Central Station:** 1,372 units → 1,372 pallets
- **Container:** 2,039 units → 1,020 pallets
- **Base:** 1,372 units → 69 pallets
- **Hydraulic Pump:** 1,372 units → 343 pallets
- **Electric Motor:** 1,372 units → 153 pallets
- **External Structure:** 1,372 units → 87 pallets
- **Electric Card:** 13,893 boxes → 186 pallets
- **Small Mechanical Units:** 401,195 boxes → 838 pallets
- **Small Electrical Units:** 628,477 boxes → 219 pallets

Buffer Stock Summary:

- **Total Buffer Inventory:** 1,053,197 pieces
- **Total Buffer Fleet Pallets:** 4,287 units

Environmental Sustainability

Ecological impacts ensure that the warehouse operations align with modern green logistics standards without sacrificing operational throughput.

Material	Carbon Footprint & Energy	Circular Economy & Lifespan	Disposal & End-of-Life	Environmental Recommendation
Wood	Low carbon footprint. Acts as carbon storage; requires low energy to manufacture.	Medium lifespan. Prone to moisture damage and mold, but easily repaired to extend operational life.	100% Biodegradable & Recyclable. Can be chipped into mulch or used for bioenergy at end-of-life.	Best overall for short-to-medium closed-loop logistics with active repair programs.
Plastic	High carbon footprint. Derived from fossil fuels; energy-intensive manufacturing process.	High lifespan. Extremely durable and does not rot, but cannot be easily repaired if structurally fractured.	Recyclable but persistent. Down cycling is possible, but cracked units often end up in landfills.	Highly favorable *only* if using 100% post-consumer recycled HDPE/PP in a strict closed-loop return system.

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Metal	Very high carbon footprint. High greenhouse gas emissions during ore extraction and smelting.	Extreme lifespan. Highly durable and virtually indestructible under normal warehouse loads.	100% Recyclable. Can be infinitely smelted down and recycled into new steel or aluminum products without quality loss.	Favorable for heavy-duty, permanent heavy-load installations where structural longevity spans decades.

Expanded Evaluation Criteria: Wood vs. Plastic vs. Metal

While the initial selection of premium wood was based primarily on cost, structural strength, and surface friction, assessing these materials through a sustainability lens reveals distinct ecological trade-offs:

To assess the real-world effectiveness of the proposed Space Utilization Efficiency (SUE) and Linear Programming (LP) models, the following Operational Optimization Framework is designed for implementation within an active warehouse environment. This framework bridges theoretical calculations with dynamic, day-to-day warehouse logistics.

Phased Implementation Strategy

To minimize operational risk, a **three-stage rollout** is recommended to transition from heterogeneous layouts to the standardized 1000mm X 900mm X 150 mm premium wooden pallet fleet.

Phase 1: Controlled Pilot & Baseline

- **Target Selection:** Isolate a single high-turnover zone (e.g., handling *Small Mechanical Units* and *Small Electrical Units*) to test the high-density stacking parameters (up to 8 and 16 layers respectively).
- **Fleet Deployment:** Introduce an initial batch of 10,000 standardized premium wooden pallets.
- **Data Logging:** Record baseline metrics regarding load stability, forklift entry speeds (utilizing the chamfered bottom boards), and exact floor space utilization prior to full configuration.

Phase 2: Full Facility Integration

- **Racking Reconfiguration:** Adjust warehouse racking slots to fit the optimal 1000mm X 900mm footprint, targeting the maximum theoretical spatial efficiency of 94.4%.
- **Fleet Scale-up:** Systematically deploy the remaining balance of the 185,663 pallets (181,376 for primary cycle/safety stock and 4,287 for buffer operations).
- **Workflow Alignment:** Train warehouse personnel on the designated material-specific vertical stacking rules (e.g., ensuring *Central Stations* and *Containers* are kept to a single-layer, non-piled configuration).

Phase 3: Dynamic Tuning & Feedback

- **Software Integration:** Integrate the SUE and LP model constraints into the active Warehouse Management System (WMS) to automate slotting decisions based on real-time inventory levels.

Operational Key Performance Indicators (KPIs)

To evaluate if the framework successfully minimizes supply chain costs and boosts throughput, the following metrics must be actively monitored:

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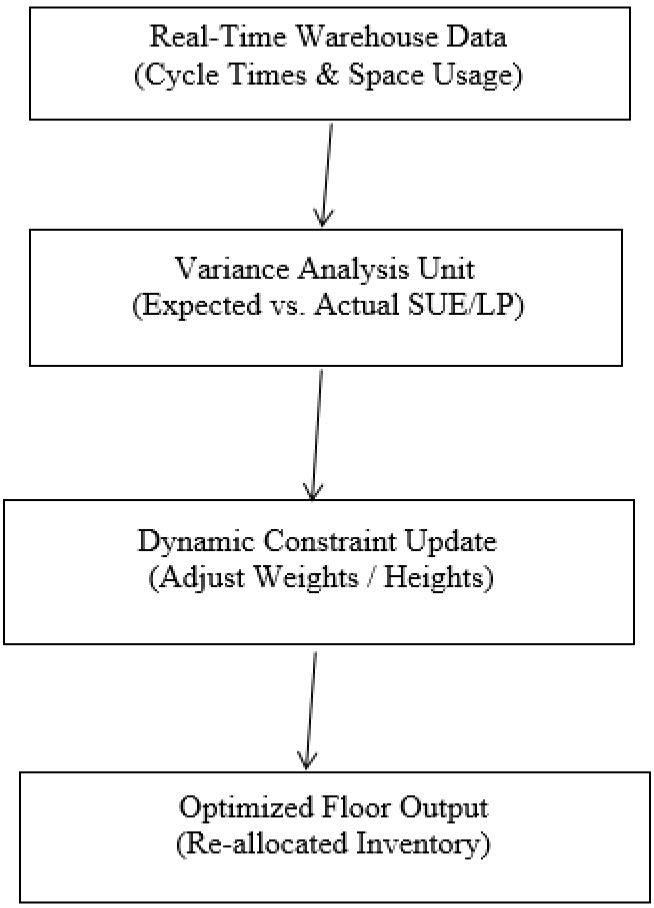
KPI Category	Metric	Operational Target	Evaluation Method
Spatial Efficiency	Floor Space Utilization	Increase by ≥15%	Weekly WMS volumetric audits comparing occupied vs. total storage capacity.
Handling Velocity	Forklift Put-away / Retrieval Time	Decrease by ≥20%	RFID/Barcode scan-to-scan time tracking for pallet moves.
Safety & Damage	Pallet-related Damage Rate	< 0.1%	Logged incidents of collapsed stacks or crushed lower packaging units.
Financial Impact	Procurement & Repair Overhead	Decrease by ≥12%	Tracking expenditures on standard wood repairs vs. historical multi-sized pallet costs.
Fleet Performance	Buffer Utilization Rate	75% - 85% active range	Real-time tracking of the 4,287 dedicated buffer units during peak hours.

Dynamic Feedback Loop & Model Refinement

To prevent the static optimization model from becoming obsolete under changing inventory profiles, a closed-loop refinement system is established:



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CONCLUSION

Standardizing material handling equipment requires balancing structural capacity with spatial configuration. By integrating mathematical space utilization techniques with realistic weight and stack parameters, this facility successfully reduces its structural footprints into a unified model.

To support the facility's master inventory matrix, procurement teams must acquire a combined total fleet of **185,663 wooden pallets** (181,376 cycle/safety units + 4,287 buffer units) measuring **900 mm × 1000 mm**. This configuration minimizes floor layout loss, standardizes logistics, and streamlines inbound and outbound workflows.

RECOMMENDATION

Implement Standardized Pallet Dimensions

To establish uniform warehouse racking configurations, eliminate floor layout loss, and simplify shelf design, the facility should standardize a single pallet footprint.

- **Recommended Specification:** Adopt premium wooden pallets measuring **1000 mm × 900 mm × 150 mm**.
- **Rationale:** Computational testing via the Space Utilization Efficiency (SUE) technique demonstrated that this specific configuration achieves up to **94.4% spatial efficiency** for core inventory components while remaining versatile enough to handle varying payload sizes.

Leverage Premium Wood as the Primary Material

While plastic and metal options offer distinct benefits (such as longevity and extreme load capabilities), **knot-free premium wood** is recommended for standard logistics handling up to 1,500 kg.

- **Key Material Enhancements:** Utilize flathead threaded screw nails to prevent loose fasteners. Ensure bottom edge boards are chamfered to allow clean, unhindered entry for pallet truck forks and reduce mechanical wear.
- **Strategic Advantage:** Wood provides the most favorable balance of high surface friction, structural strength, widespread availability, low upfront cost, and ease of repair.

Procure a Total Fleet of 185,663 Standardized Pallets

To fully satisfy the facility's inventory demands across its nine distinct material classes without causing operational bottlenecks, procurement should acquire a combined fleet of **185,663 pallets**, strictly segmented into two functional pools:

- **Primary Fleet (Cycle & Safety Stock): 181,376 units** to support daily storage matrices under defined vertical stacking, weight (1500 kg limit), and height (1000 mm limit) boundaries.
- **Backup Fleet (Dedicated Buffer Operations): 4,287 units** to smoothly manage fluctuating labor run-times and operational buffer windows.

Operationalize Material-Specific Storage Constraints

To ensure warehouse safety and structural integrity, stacking workflows must adhere to the specific limits derived from the inventory model:

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