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Warehouse Layout Improvement and Routing Optimization: A Comprehensive Approach To Picking Process Efficiency

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Abstract
Purpose – This study investigates warehouse layout optimisation and picking-route efficiency within the telecommunications sector, where logistics operations represent a significant proportion of operational costs. The research aims to identify how systematic product repositioning and algorithmic routing can reduce travel distances, labour costs, and storage requirements in a medium-sized Portuguese telecommunications company.
Design/methodology/approach – An action-research methodology was employed, combining ABC classification analysis, layout restructuring simulation, and nearest-neighbour routing algorithm implementation. Data collection drew on picking records, time studies, and ERP data from nine representative customer orders. Cost-benefit analysis estimated the financial impact of proposed changes against implementation costs.
Findings – Layout reorganisation alone reduced average travel distance per order by 72% (from 167.8 m to 46.8 m); routing algorithm implementation alone achieved a 54% reduction; combined application of both interventions yielded a 66% reduction – lower than the isolated layout gain because the algorithm operates on already-shortened distances in the optimised configuration. Annual labour cost savings reached €3,523.76 and 479.6 hours of picking time were recovered. Pallet utilisation fell by 74% (257 to 68), reducing storage costs by €1,134 annually. All figures are simulation-based estimates from a single case study; no formal statistical testing was conducted.
Originality – The study offers a replicable, low-investment optimisation framework for small to medium-sized logistics operations, demonstrating the complementary and synergistic effects of integrated layout redesign and algorithmic routing. The findings are relevant to regional SME competitiveness and operational sustainability in logistics-intensive sectors.

Keywords: Warehouse management; Picking optimization; Layout restructuring; ABC classification; Routing algorithms; Telecommunications logistics; Operational efficiency

Paper type: Original Research Article

1. Introduction

The contemporary business environment is characterized by rapid technological advancement, increasing globalization, and evolving consumer expectations that collectively intensify competitive pressures across all industrial sectors (Frikha & Hlali, 2023). Within this dynamic landscape, operational efficiency has emerged as a fundamental determinant of organizational sustainability and market competitiveness (Mansidão, 2017). The logistics function, in particular, has evolved from a purely operational role to a strategic capability that can significantly differentiate companies from their competitors (Marchesini & Alcântara, 2012; Pinto, 2019).

Logistics costs typically constitute a substantial proportion of total production costs, with warehouse operations representing one of the most significant components of logistics expenditure (Rouwenhorst et al., 2000; Miranda, 2016). Research indicates that in many industries, logistics costs can account for 15-25% of total operational expenses, making this area particularly attractive for cost reduction initiatives and efficiency improvements (Sardinha, 2017). Moreover, as products become increasingly commoditized in terms of price, features, and quality, the differentiation of service through superior logistics performance has become a critical competitive advantage (Miranda, 2016; Menezes, 2012).

The telecommunications sector presents unique logistics challenges due to the diversity of products handled, ranging from small components such as cables and connectors to large equipment installations, combined with increasingly demanding customer expectations for rapid response times (Santos et al., 2009). This sector's logistics operations must balance inventory levels, space utilization, order fulfillment speed, and cost efficiency while maintaining high service quality standards. The picking process, which involves retrieving products from storage locations to fulfill customer orders, emerges as particularly critical, representing

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approximately 55% of total warehouse operating costs, with travel time accounting for about 50% of picking costs (Bottani et al., 2019; Koster et al., 2007).

The increasing diversity of products and the pressure to achieve shorter response times place evident strain on logistics operations, highlighting the necessity of establishing effective and efficient logistics operations to ensure organizational competitiveness (Teixeira, 2018). Recent studies have demonstrated that warehouse layout optimization and advanced routing strategies can significantly reduce picking times and operational costs while improving order accuracy and employee satisfaction (De Koster et al., 2007; Fernandes, 2017). Furthermore, the integration of data analytics and algorithmic approaches to warehouse management has opened new possibilities for systematic optimization that were previously unattainable (Lai, 2022; Hódosi et al., 2023).

Despite the recognized importance of warehouse optimization, many companies, particularly in emerging markets and small to medium-sized enterprises, continue to operate with suboptimal layouts and inefficient picking processes (Leite, 2017). This gap between theoretical knowledge and practical implementation represents both a challenge and an opportunity for applied research that can bridge academic findings with real-world applications. The present study addresses this gap by conducting a comprehensive analysis of logistics optimization opportunities within a telecommunications company operating in Portugal.

This research was conducted at a Portuguese company specializing in innovative engineering and technology solutions across the energy, telecommunications, and infrastructure sectors. The company, founded in 1984 and currently operating in 11 countries with over 1,700 employees, faces typical challenges of a growing organization: increasing product diversity, expanding geographic coverage, and rising customer expectations for service quality and delivery speed. The study focuses specifically on optimizing the company's warehouse operations, with particular emphasis on the picking process, layout configuration, and product storage strategies.

The research objectives were structured around three primary goals. First, to conduct a comprehensive analysis of current warehouse operations to identify inefficiencies and optimization opportunities. Second, to develop and evaluate concrete proposals for warehouse layout restructuring based on product rotation analysis and optimal space utilization principles. Third, to design and test a routing algorithm that optimizes picking paths, reducing travel distances and time requirements. Additionally, complementary objectives included implementing product identification systems, establishing visual management practices, and developing proposals for specialized storage solutions for specific product categories.

The significance of this research extends beyond the immediate benefits to the case study organization. The methodologies employed, analytical approaches developed, and solutions implemented provide a replicable framework for similar optimization projects in other telecommunications companies and related sectors. Furthermore, the study contributes to the growing body of empirical evidence regarding the practical application of warehouse optimization theories, particularly in the context of small to medium-sized enterprises in emerging markets where such research remains relatively scarce (Costa, 2020; Santos, 2021).

The remainder of this paper is organized to provide a comprehensive understanding of the research process and findings. The following sections integrate theoretical foundations with methodological descriptions, present detailed results including quantitative analyses and simulations, discuss the implications of findings in relation to existing literature, and conclude with practical recommendations for implementation and future research directions. Through this integrated approach, the study demonstrates how systematic analysis combined with algorithmic optimization can yield significant improvements in warehouse operations, contributing to enhanced organizational competitiveness and operational sustainability.

2. Theoretical foundation and research methodology

2.1 Logistics evolution and strategic importance

The evolution of logistics as a strategic business function reflects broader transformations in global commerce and industrial organization. Historically, logistics was viewed primarily as a tactical function focused on transportation and storage (Santos et al., 2009). However, contemporary understanding recognizes logistics as a strategic capability encompassing planning, implementation, and control of efficient material flows and information systems to meet customer requirements while minimizing total costs (Council of Logistics Management, 2013). This evolution has progressed through distinct phases, from basic distribution management to integrated supply chain coordination and, more recently, to digitally enabled smart logistics systems (Pinto, 2019; Frikha & Hlali, 2023; Alsakhen et al., 2024).

The strategic importance of logistics stems from its impact on both cost structures and service quality. Research consistently demonstrates that companies with superior logistics capabilities achieve better financial performance, higher customer satisfaction, and stronger competitive positions (Mansidão, 2017; Marchesini & Alcântara, 2012). In the telecommunications sector specifically, efficient logistics operations enable rapid deployment of infrastructure, minimize equipment downtime, and support the high service levels that customers increasingly demand. The ability to efficiently manage diverse product portfolios, from small components to large installations, while maintaining inventory accuracy and minimizing handling costs, has become a key differentiator among telecommunications service providers (Sardinha, 2017).

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2.2 *Warehouse management and layout optimization*

Warehouse layout design represents one of the most fundamental decisions in warehouse management, with long-lasting implications for operational efficiency and cost structure (Rouwenhorst et al., 2000). An effective warehouse layout must balance multiple objectives: minimizing travel distances, maximizing space utilization, facilitating material flow, ensuring ergonomic working conditions, and maintaining flexibility for future changes (Filho & Malagutti, 2017; Santos, 2019). The literature identifies several key principles for warehouse layout optimization. First, products should be positioned based on their rotation frequency,

Recent research has advanced beyond simple ABC classification to consider multiple dimensions of product characteristics simultaneously. Multi-criteria classification approaches incorporate factors such as weight, volume, fragility, and complementarity alongside rotation frequency to optimize storage decisions (Costa, 2020). Additionally, dynamic classification systems that adjust product positioning based on seasonal variations or trend analysis have shown promise in maintaining optimal layouts over time (Ferraz, 2020). The integration of warehouse management systems (WMS) with real-time data analytics enables continuous optimization of storage locations, though implementation challenges remain significant for many organizations (Mesquita, 2021; Udvardy et al., 2024).

2.3 *Picking process optimization*

The picking process, defined as the retrieval of products from storage locations to fulfill customer orders, represents the most labor-intensive and costly warehouse operation (De Koster et al., 2007). Research consistently identifies picking as accounting for 50-55% of total warehouse operating costs, with travel time representing the dominant component of picking time (Bottani et al., 2019; Fernandes, 2017). This cost structure makes the picking process a primary target for efficiency improvement initiatives, where even modest percentage improvements can yield substantial cost savings and productivity gains.

Picking operations can be categorized along several dimensions that affect efficiency. Single-order picking, where one operator collects all items for one order at a time, offers simplicity and accuracy but may be inefficient for small orders. Batch picking, where multiple orders are processed simultaneously, can reduce travel distances but introduces complexity in order consolidation. Zone picking assigns operators to specific warehouse areas, potentially reducing congestion but requiring coordination mechanisms (Escobar, 2012). The selection of picking strategy must consider order profiles, warehouse layout, product characteristics, and available technology.

Routing strategy represents another critical dimension of picking efficiency. Common routing methods include S-shape routing (traversing aisles completely), return routing (entering and exiting aisles from the same end), midpoint routing (entering aisles only to the midpoint), largest gap routing (skipping aisles with no picks), and optimal routing based on algorithms (De Koster et al., 2007; Santos, 2015). Research demonstrates that optimal routing can reduce travel distances by 20-50% compared to simple heuristics, though the computational complexity of true optimal routing increases rapidly with order size (Duarte et al., 2019).

Technology integration in picking operations has expanded significantly in recent years. Barcode scanning and RFID systems improve accuracy and enable real-time inventory tracking (Sousa, 2018; Das et al., 2025). Pick-to-light and voice-directed picking systems can increase productivity and reduce errors compared to paper-based systems (Mesquita, 2021). Mobile computing devices with route optimization software provide dynamic routing guidance adapted to current warehouse conditions (Lai, 2022). However, technology implementation must be carefully planned considering organizational readiness, cost-benefit analysis, and integration with existing systems.

2.4 *Research methodology and approach*

This research employed an action research methodology, characterized by collaborative problem-solving between researchers and practitioners in real organizational settings (Coutinho et al., 2009; Pereira & Oliveira, 2021). Action research is particularly appropriate for logistics optimization studies where the goal is both to understand phenomena and to generate practical improvements. The methodology consists of iterative cycles of planning, action, observation, and reflection, enabling continuous refinement of proposed solutions based on empirical results.

The research process began with an extensive diagnostic phase involving direct observation of warehouse operations, analysis of operational data, interviews with warehouse personnel, and review of existing procedures and documentation. This phase aimed to develop comprehensive understanding of current operations, identify inefficiencies and improvement opportunities, and establish baseline performance metrics. The 5W2H methodology (What, Why, Who, Where, When, How, How much) was employed to systematically structure problem identification and solution development (Torres, 2019).

Data collection encompassed multiple sources and methods to ensure comprehensive coverage. Quantitative data included

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detailed picking records for a representative sample of customer orders, warehouse layout dimensions and storage locations, product rotation statistics from the ERP system, time studies of picking operations, and cost data for labor and storage resources. Qualitative data collection involved structured observations of picking processes, semi-structured interviews with warehouse operators and managers, and review of documented procedures and problems. This multi-method approach enabled triangulation of findings and validation of proposed solutions from multiple perspectives.

The analytical approach integrated several complementary techniques. ABC classification analysis categorized products based on picking frequency to identify high-priority items for optimal placement. Layout simulation compared current and proposed configurations using distance calculations for representative order samples. Algorithm development created a nearest neighbor routing optimization tool implemented in a spreadsheet environment for accessibility and ease of modification. Cost-benefit analysis estimated financial impacts of proposed changes considering implementation costs and ongoing savings. Time studies measured task durations for baseline and improved scenarios to quantify productivity improvements.

The study focused on the warehouse area dedicated to customer network equipment, which represents the highest volume and most time-sensitive operations within the facility. This scope limitation enabled detailed analysis while maintaining manageability of the research project. However, the methodologies and tools developed are designed to be generalizable to other warehouse areas and potentially to other similar organizations.

The research design incorporates both ex-ante simulation and ex-post validation approaches. Proposed improvements were first evaluated through simulation using historical data, then selected improvements were implemented and monitored to validate predicted benefits. This combination of simulation and real-world testing provides both efficiency in solution development and confidence in results. The iterative nature of action research enabled refinement of solutions based on implementation experience, addressing practical considerations that emerged during deployment.

3. Current situation analysis and problem identification

3.1 Organizational context

The company operates as a shared services organization providing logistics support to multiple business units across the telecommunications, energy, and smart cities sectors. The warehouse facility analyzed in this study represents a modern installation with approximately 2,000 square meters of storage space organized in a rack-based configuration. The facility manages inventory for client network operations, including diverse products ranging from small components like HDMI cables and cable ties to large items such as optical network terminals (ONTs), customer premises equipment (CPE), and cable reels.

An important characteristic of the logistics operation is that approximately 60% of materials used are consigned by clients, primarily major telecommunications operators. This consignment arrangement places particular emphasis on inventory accuracy, rapid order fulfillment, and minimal handling costs, as service level agreements specify strict deadlines for equipment delivery and limit acceptable storage durations for client-owned inventory. The warehouse operates using Microsoft Dynamics NAV as its enterprise resource planning (ERP) system, providing basic inventory tracking but limited advanced warehouse management capabilities.

The picking process follows a traditional paper-based workflow. Customer requisitions are printed and distributed to warehouse operators who manually collect required items using hand trolleys. After collection, operators return to a designated area to scan serialized equipment and confirm quantities in the system. Orders are staged overnight and collected the following day by installation teams. This process, while functional, exhibited several inefficiencies that motivated the optimization study.

3.2 Identified problems and their consequences

Systematic observation and data analysis revealed multiple interconnected problems affecting warehouse efficiency. Product location accuracy represented a significant issue, with system records frequently not reflecting actual physical locations. This inaccuracy resulted from products being relocated during daily operations without corresponding system updates, creating a vicious cycle where operators distrusted system information and increasingly relied on memory and visual searching. The consequence was extended picking times, increased movement, and higher error rates as operators searched for items.

Storage rack identification proved inadequate or absent in many areas. Racks lacked consistent labeling schemes, and when labels existed they often used non-intuitive codes that required memorization. This problem particularly affected new employees requiring extended training periods to achieve productivity, and contributed to picking errors when operators confused similar rack designations. The lack of clear identification also complicated communication between shifts and made it difficult to efficiently direct external contractors who occasionally assisted with warehouse operations.

Product positioning within the warehouse revealed significant inefficiencies. ABC analysis demonstrated that many high-

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rotation products occupied distant storage locations requiring extended travel distances for frequent picks. Conversely, low-rotation items occupied prime locations near shipping areas. For example, corridor AK, located farthest from the picking staging area, contained products generating 15,363 picking lines annually, while corridor AM, closest to staging, handled only 592 picking lines. This misalignment directly increased picking distances and times, representing perhaps the single largest opportunity for efficiency improvement.

The picking equipment used consisted of second-hand trolleys acquired from a laundry service, which proved ill-suited for warehouse operations. The trolleys featured tall, narrow configurations that made them unstable when loaded with diverse products. Products frequently required rearrangement during picking to maintain stability and prevent damage. Small items lacked appropriate compartments, requiring operators to collect cardboard boxes for containment. The trolley frame design, particularly cross-bracing, obstructed barcode scanning, requiring product removal for successful scans. These equipment limitations added unnecessary handling time and contributed to operator fatigue.

Pick routing represented another major inefficiency. Customer requisitions listed products in arbitrary order, typically following the sequence in which customers entered requirements rather than any logical warehouse sequence. Operators attempted to mentally optimize routes by skipping around the pick list to collect nearby items together, but this approach proved error-prone for larger orders and required repeatedly reviewing the requisition to ensure all items were collected. The lack of systematic routing guidance resulted in inefficient paths with frequent backtracking and repeated visits to the same aisles.

Process design separated product collection from system confirmation. Operators first collected all items for an order, then returned to a fixed location to scan serialized equipment. This separation increased total process time and created problems when similar products required differentiation during scanning. For example, multiple variants of optical network terminals with nearly identical appearances caused scanning errors requiring process restart, particularly frustrating given the time already invested in collection.

Space utilization analysis revealed suboptimal storage density. Products of similar types or complementary usage were scattered across multiple locations, requiring more storage positions than necessary. The current configuration utilized 257 pallets for inventory storage, representing substantial ongoing costs and limiting capacity for inventory growth. Additionally, large items such as cable reels occupied outdoor storage areas not well-integrated with the main warehouse flow, creating additional handling steps and exposure to weather-related damage.

4. Proposed solutions and implementation

4.1 ABC classification and product positioning strategy

The foundation of the warehouse optimization strategy rested on comprehensive ABC classification of all products based on picking frequency. Analysis of historical data from 2023 identified picking line frequency for each product, representing the number of times operators visited each storage location to collect items regardless of quantity per visit. This metric proved more appropriate than value or volume for optimizing picking efficiency, as travel distance depends on frequency of visits rather than amount collected per visit.

The analysis classified 232 distinct products into three categories following the ABC classification approach described in Section 2.2. Class A contained 60 products (26% of total) generating the highest picking frequency. Class B included 48 products (21% of total) with moderate picking frequency. Class C comprised 124 products (53% of total) with low picking frequency. The observed distribution (26–21–53) differed from the classical 20–30–50 Pareto proportions, reflecting the specific characteristics of the telecommunications equipment product mix.

Corridor-level analysis revealed the magnitude of current inefficiency. The existing configuration showed corridor AK (farthest from staging) handling 15,363 picking lines annually, corridor AL with 10,078 lines, and corridor AM (closest to staging) with only 592 lines. The proposed reorganization dramatically redistributed this activity: corridor AM would increase to 25,550 lines (43-fold increase), corridor AL to 6,814 lines, and corridor AK to only 1,284 lines (92% reduction). This reallocation directly translated to reduced travel distances as high-frequency picks concentrated near the staging area.

The detailed product positioning strategy considered multiple factors beyond simple ABC classification. Products with complementary usage (items frequently ordered together) were positioned in close proximity to enable efficient batch collection. Product physical characteristics including size and weight influenced vertical positioning, placing heavy or bulky items at convenient heights. The strategy also maintained some flexibility for seasonal variations and new product introductions by designating overflow positions in each zone.

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4.2 *Layout restructuring proposals*

Based on ABC classification and detailed simulation analysis, three progressive layout modification proposals were developed. The first phase focused on product repositioning within the existing rack structure. This reorganization required no capital investment, only labor time for product movement. Simulation using representative order samples demonstrated that this repositioning alone would reduce average picking distance by approximately 72%, from 167.8 meters to 46.8 meters per order. Annual distance savings would total 262,199.52 meters, equivalent to 479.6 hours of walking time valued at €3,523.76 in labor costs.

Space utilization analysis revealed significant consolidation opportunities. The current configuration utilized 257 pallets distributed across corridors, with corridor AK requiring 63 pallets, AM requiring 54, and AL requiring 36. Detailed product-by-product analysis showed that consolidating related products and optimizing pallet utilization could reduce total pallet requirements to 68, representing a 74% reduction. Corridor AM would require 38 pallets, AL would need 24, and AK and AJ each would use 3. This consolidation reduced annual storage costs from €1,542 to €408, saving €1,134 annually while freeing substantial space for future growth.

The second phase proposed expanding rack capacity in high-activity corridors. Analysis identified opportunities to install additional rack modules in corridors AM and AL without compromising aisle widths or material handling equipment maneuverability. This expansion would accommodate more Class A products in prime locations and provide additional buffer capacity. The capital cost for this expansion was estimated at €12,000 for rack acquisition and installation, with payback period of approximately 3.4 years based on ongoing storage cost savings and efficiency gains.

The third phase addressed material flow optimization through receiving and shipping area reorganization. The current configuration positioned both receiving and shipping at the same end of the warehouse, creating congestion and inefficient flow patterns. The proposal relocated receiving to one end and shipping to the opposite end, establishing a through-flow pattern that eliminated backtracking and segregated incoming from outgoing traffic. This modification required no structural changes, only designation of different dock areas for each function, but significantly improved traffic flow and reduced congestion during peak periods.

4.3 *Routing algorithm development and implementation*

A nearest neighbor routing algorithm was developed to optimize pick paths through the warehouse. The algorithm operates by calculating distances between all required pick locations and the current position, then selecting the closest unvisited location as the next destination. This greedy heuristic approach does not guarantee globally optimal solutions but typically generates near-optimal routes with minimal computational requirements, making it suitable for real-time application in warehouse environments where order composition varies continuously.

The algorithm implementation incorporated warehouse-specific constraints and features. The distance calculation considered aisle configuration, one-way traffic restrictions, and physical barriers, generating realistic travel distance estimates rather than simple Euclidean distances. The algorithm accommodated the warehouse's combination of traversable aisles (where complete traversal is efficient) and return aisles (where entering only to reach specific locations is optimal). Product characteristics such as weight and fragility influenced sequencing to ensure heavy or fragile items were collected appropriately.

Testing of the routing algorithm used nine representative customer requisitions selected to span the range of order sizes and product mixes encountered in normal operations. These orders ranged from simple requests for a few items to complex orders requiring products from multiple warehouse zones. For each requisition, baseline performance was established by observing and timing actual operator execution following current practices. Then the algorithm generated optimized sequences, and simulated performance was calculated using measured travel speeds and handling times.

Results demonstrated substantial improvements across all test requisitions. Average distance reduction was 54%, declining from 361,461.60 meters annually under current routing to 165,854.40 meters with algorithm guidance. Time savings averaged 94 minutes daily (413.6 hours annually), directly reducing labor costs by approximately €3,031.25 per year. Individual requisition improvements ranged from 47% to 68% distance reduction, with larger, more complex orders showing greater absolute savings while smaller orders showed higher percentage improvements.

The algorithm was implemented in a spreadsheet environment for accessibility and ease of modification. Operators could input required product locations using simple selection boxes, and the algorithm automatically generated the optimal sequence with visual route display and distance calculation. This implementation approach avoided complex integration with the ERP system while still providing immediate practical benefits. Future integration with the NAV system could automate the process further, but the standalone tool provided value immediately with minimal implementation cost.

Combined implementation of layout restructuring and routing optimization yielded even more impressive results. When algorithm-optimized routing was applied to the proposed layout configuration, total annual distance declined to 123,098.40 meters, representing 66% reduction compared to the current baseline. This combined approach reduced annual labor costs by €3,523.76 (48% reduction) while simultaneously improving order accuracy through more systematic picking processes. The

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complementary nature of layout optimization and routing improvement demonstrates the value of integrated approaches to warehouse optimization.

4.4 Complementary improvements

Several complementary improvements were implemented to support the core optimization initiatives. A systematic rack identification system was established using clear, logical designations visible from multiple angles. Color coding differentiated major warehouse zones to facilitate navigation and reduce errors. Product location labels were redesigned to include bar codes, product descriptions, and location codes, improving accuracy and reducing time required for identification. These relatively simple changes significantly improved warehouse navigability particularly for new employees and temporary personnel.

Cable reel management received special attention due to the challenges of storing and handling these large, heavy items. An identification system using colored tags was implemented to indicate reel age and enable first-in-first-out rotation, reducing waste from cable deterioration. Proposals were developed for dedicated outdoor storage racks specifically designed for cable reels, which would improve organization, reduce handling damage, and free indoor space for higher-value products. The estimated investment of €6,000 for specialized cable storage racks would be offset by reduced product damage and improved space utilization.

Picking equipment replacement was proposed to address the limitations of the existing trolleys. Research identified purpose-designed picking carts featuring multiple compartments for different product sizes, smooth-rolling wheels for reduced operator fatigue, and open frame design facilitating barcode scanning. While requiring capital investment of approximately €2,500 for sufficient carts, the improved equipment would reduce picking time, minimize product damage, and improve operator satisfaction, with payback estimated at under two years through productivity improvements and reduced error correction costs.

5. Quantitative results and performance analysis

5.1 Layout optimization results

The layout restructuring analysis produced compelling quantitative evidence of improvement potential. Baseline measurements of the current configuration showed an average travel distance of 167.8 meters per order for the representative sample of nine customer requisitions. Total annual distance for these requisitions alone was calculated at 44,133 meters. When the same requisitions were simulated using the proposed product locations, average distance decreased to 46.8 meters per order, reducing total annual distance to 12,328 meters. This represented a 72% reduction in travel distance specifically attributable to improved product positioning.

Time analysis complemented the distance measurements. Using established time standards of 1.2 meters per second walking speed and appropriate allowances for product handling, the current configuration required an average of 8 minutes 20 seconds per order for the collection phase alone. The optimized layout reduced this to 2 minutes 20 seconds, saving 6 minutes per order or 25,200 minutes (420 hours) annually for the sample orders. Extrapolated across the full workload, this represented substantial labor cost savings while also improving service responsiveness.

Storage efficiency improvements were equally impressive. The detailed product-by-product allocation analysis demonstrated that the existing 257 pallet positions could be consolidated to 68 positions through three mechanisms. First, grouping complementary products that were previously scattered reduced the number of partial-pallet positions. Second, optimizing pallet utilization factors by carefully planning product arrangements increased average pallet fullness from 61% to 89%. Third, concentrating high-rotation items in fewer locations freed distant racks for decommissioning or repurposing. The 74% reduction in pallet requirements translated directly to annual storage cost savings of €1,134 and freed valuable floor space for expansion or alternative uses.

Corridor-level activity redistribution provided striking evidence of the misalignment between current layout and actual picking patterns. The existing configuration concentrated 45% of picking activity in the two most distant corridors (AK and AL), requiring 25,441 picks from remote locations. The optimized layout reversed this distribution, concentrating 75% of picks in the nearest corridor (AM), with only 6% of picks requiring access to distant corridors. This radical redistribution of activity directly reduced average travel distance per pick from 8.2 meters to 2.3 meters, demonstrating the power of systematic analysis and planning in layout design.

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5.2 Routing algorithm performance

The routing algorithm testing revealed consistent and substantial performance improvements across all requisitions analyzed. Detailed results for each of the nine test requisitions demonstrated the algorithm's effectiveness across varying order sizes and complexity levels. Requisition 1, a relatively simple order requiring 5 picks, showed distance reduction from 193.3 meters to 65.1 meters (66% improvement) and time savings of 6 minutes 16 seconds. Requisition 4, a more complex order with 15 picks, demonstrated distance reduction from 167.8 meters to 63.0 meters (62% improvement) and time savings of 27 minutes 4 seconds.

Aggregate analysis across all nine requisitions showed average distance reduction of 54%, from 1,434.0 meters total current distance to 658.2 meters with algorithm optimization. Average time per requisition decreased from 13 minutes 20 seconds to 6 minutes 9 seconds, saving 7 minutes 11 seconds per order. Projecting these improvements across annual order volume of approximately 2,640 requisitions (based on 264 working days and average 10 daily requisitions), total annual distance savings would reach 215,167.93 meters, equivalent to 413.6 hours of walking time valued at €3,031.25 in labor costs.

Analysis of algorithm performance characteristics revealed several important patterns. Larger orders showed greater absolute time savings, as more picks provided more opportunities for routing optimization. However, smaller orders often showed higher percentage improvements, as even minimal inefficiency in simple routes became apparent through optimization. The algorithm proved particularly effective for orders requiring products from multiple corridors, where current practice often involved repeated visits to the same areas. Orders concentrated in single corridors showed more modest improvements, as the opportunity for optimization was inherently limited.

The interaction between routing algorithm and layout structure demonstrated important complementarity. When algorithm-optimized routing was applied to the current layout, average distance per requisition declined from 159.6 meters to 73.1 meters (54% reduction). When the same algorithm was applied to the proposed optimized layout, average distance further declined to 49.9 meters, representing 69% reduction compared to current baseline with current routing. This combined improvement exceeded the sum of independent improvements, indicating synergistic effects where optimal routing can better exploit an optimized layout structure.

5.3 Combined implementation analysis

The full potential of the optimization program emerged through combined analysis of layout restructuring and routing algorithm implementation. The baseline scenario (current layout with current routing practices) showed average distance of 159.6 meters per requisition and total annual distance of 361,461.60 meters for the warehouse's typical order volume. The layout-only optimization scenario reduced this to 123,098.40 meters annually (66% reduction). The routing-only scenario achieved 165,854.40 meters annually (54% reduction). The combined scenario, implementing both layout optimization and routing algorithm, achieved 123,098.40 meters annually (66% reduction).

Time savings analysis reinforced these findings. Current operations consumed approximately 1,027 hours annually in product collection activity. Layout optimization alone would reduce this to 548 hours (47% reduction). Routing optimization alone would achieve 614 hours (40% reduction). Combined implementation would require only 547 hours (47% reduction), yielding annual time savings of 480 hours valued at €3,523.76 assuming fully loaded labor costs of €7.34 per hour including benefits and overhead.

Cost analysis considered both direct and indirect benefits. Direct labor cost savings of €3,523.76 annually represented the largest quantifiable benefit. Storage cost reduction of €1,134 annually from pallet consolidation provided additional recurring savings. Productivity improvements enabled faster order processing, potentially allowing the warehouse to handle increased volume without proportional staff increases, though this capacity benefit was not formally quantified. Quality improvements from reduced operator fatigue and more systematic processes would reduce error rates and associated correction costs, estimated conservatively at €500-1,000 annually. Employee satisfaction and retention benefits were expected but not quantified.

Investment requirements for implementation were modest given the magnitude of benefits. Layout restructuring required primarily labor time for product movement, estimated at 80 labor hours costing approximately €587. Rack identification materials totaled €200. Algorithm implementation in spreadsheet format required approximately 40 hours of development time (€293) but no software licensing costs. Total core implementation investment of €1,080 would be recovered in approximately 3 months through direct cost savings alone, representing exceptional return on investment. Optional enhancements including specialized picking carts (€2,500) and cable storage racks (€6,000) offered longer payback periods of 2-3 years but would provide ongoing benefits beyond initial savings.

Table 1 summarises the key before/after performance indicators across the three intervention scenarios. All figures derive from simulation and time-study data (n = 9 requisitions); no formal statistical testing was conducted.

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Table 1. Summary of performance indicators: baseline vs. optimised scenarios

Indicator	Baseline	Layout only	Algorithm only	Combined
Avg. distance / order (m)	167.8	46.8 (−72%)	73.1 (−54%)	49.9 (−66%)
Annual distance (m)	361,462	123,098	165,854	123,098
Annual picking hours	1,027	548 (−47%)	614 (−40%)	547 (−47%)
Annual labour saving (€)	–	3,523.76	3,031.25	3,523.76
Pallets required	257	68 (−74%)	n/a	68 (−74%)
Storage cost saving (€/yr)	–	1,134	–	1,134

5.4 Validation and implementation experience

Partial implementation during the study period provided real-world validation of predicted benefits. The company initiated product repositioning in corridor AM based on ABC classification analysis, relocating approximately 30% of high-rotation items to closer locations. Monitoring during this partial implementation showed picking distance reduction averaging 35-40% for orders involving repositioned products, consistent with simulation predictions. Operator feedback was positive, noting reduced walking fatigue and faster order completion times.

Implementation challenges emerged primarily in change management rather than technical execution. Warehouse operators initially resisted changing familiar product locations, requiring several training sessions to explain the rationale and benefits of reorganization. The ERP system updates to reflect new locations required careful coordination to avoid creating temporary location inaccuracy during transition. Development of systematic relocation procedures including verification steps proved essential to maintain accuracy during the reorganization process.

The routing algorithm implementation revealed both strengths and limitations of the spreadsheet-based approach. Positive aspects included ease of use requiring minimal training, transparency of route calculation enabling operator understanding and acceptance, and flexibility for rapid modification as warehouse conditions changed. Limitations included manual data entry requirement for each order, potential for transcription errors, and lack of integration with the ERP system requiring duplicate documentation. Despite these limitations, operators found the tool valuable and used it regularly for complex orders where routing optimization provided greatest benefit.

Long-term sustainability considerations emphasized maintaining the improvements achieved. Periodic review of product classifications was recommended to adapt to changing demand patterns. Discipline in maintaining location accuracy required ongoing emphasis and occasional audits. The spreadsheet-based routing tool required periodic updates to reflect any layout changes or new product additions. These maintenance requirements were modest compared to ongoing benefits but required management attention to ensure persistence of improvements.

6. Discussion and theoretical implications

6.1 Contribution to warehouse optimization literature

This study contributes to warehouse optimization literature through empirical validation of theoretical principles in a real-world telecommunications logistics setting. The results strongly confirm established principles regarding the importance of ABC-based product positioning, showing that strategic product placement based on rotation frequency can reduce travel distances by over 70% (Vieira et al., 2021; Teodoro, 2016). The magnitude of improvement observed surpasses many reported in literature, likely due to the particularly suboptimal initial

The study extends existing knowledge by demonstrating the synergistic effects of combined layout and routing optimization. The combined improvement (66%) exceeded either intervention in isolation (54% for routing alone, 72% for layout alone in isolation scenarios), suggesting that these approaches are complementary rather than simply additive. This finding has important implications for research and practice, indicating that warehouse optimization should pursue multiple improvement dimensions simultaneously rather than sequentially to maximize benefits.

The research also contributes methodologically by demonstrating the viability of relatively simple analytical approaches for warehouse optimization. While advanced warehouse management systems and sophisticated optimization algorithms offer theoretical advantages, this study shows that substantial improvements can be achieved using basic classification analysis, spreadsheet-based simulation, and simple heuristic routing. This finding is particularly relevant for small to medium-sized enterprises and organizations in developing markets where sophisticated software investments may be difficult to justify.

6.2 Practical implications for logistics management

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The findings offer several important practical implications for logistics managers. First, the results emphasize the value of systematic data analysis in identifying improvement opportunities. Many warehouses operate for years without thorough analysis of product rotation patterns and their alignment with physical layout. The observation that the company had extremely high-rotation products in distant locations suggests this problem may be widespread, arising from incremental decisions over time without periodic comprehensive review. Organizations should implement regular layout audits comparing actual picking patterns with theoretical optimal configurations.

Second, the study demonstrates that significant improvements can be achieved with minimal capital investment when organizations leverage existing resources intelligently. The core layout optimization required only labor time for product relocation, while the routing algorithm was implemented in spreadsheet format accessible to operators. This contrasts with the substantial investments often associated with warehouse optimization through automation or advanced systems. While such investments may be appropriate in some contexts, this research shows that analytical approaches can deliver substantial value independent of capital expenditure.

Third, the importance of operator engagement in optimization initiatives emerged clearly during implementation. Initial resistance to changing familiar product locations and processes threatened adoption despite the clear benefits demonstrated through analysis. Success required transparent communication about the rationale for changes, involvement of operators in planning implementation details, and patience in allowing adjustment to new procedures. Managers pursuing similar initiatives should allocate substantial attention to change management aspects, not merely technical optimization.

Fourth, the research highlights the value of iterative implementation approaches that allow learning and adjustment. Beginning with partial implementation in one corridor provided proof of concept, generated operator buy-in through demonstrated results, and revealed practical issues requiring attention before full deployment. This incremental approach reduced implementation risk while still delivering measurable benefits relatively quickly. Organizations should consider phased implementation strategies that build momentum through early successes rather than attempting comprehensive simultaneous changes.

6.3 Contextual factors and generalizability

Several contextual factors influenced this study's results and affect generalizability to other settings. The telecommunications equipment product mix features moderate product diversity (232 SKUs), relatively stable demand patterns, and low perishability, facilitating ABC classification and layout planning. Industries with higher product diversity, highly variable demand, or perishable products might face greater challenges in achieving similar improvements. However, the fundamental principles of rotation-based positioning and systematic routing remain applicable across contexts even if specific benefit magnitudes vary.

The warehouse physical configuration influenced achievable improvements. The rack-based system with defined corridors facilitated clear routing paths and enabled precise distance calculations. Warehouses with more complex configurations including multi-level mezzanines, intersecting aisles, or irregular layouts might find route optimization more challenging. Similarly, the specific ratio of high-rotation to low-rotation products affects potential layout improvement magnitude; warehouses with more uniform rotation patterns across products would see smaller benefits from repositioning.

Organizational factors also shaped the study. PROEF's willingness to experiment with changes, availability of historical data for analysis, and relatively stable workforce all facilitated the research and implementation. Organizations with higher employee turnover, limited data availability, or rigid operational procedures might face greater implementation challenges. The presence of performance pressure from client service level agreements provided motivation for improvement but also required careful coordination to avoid service disruptions during implementation.

Despite these contextual factors, the core methodologies and principles appear broadly applicable. The ABC classification approach can be adapted to various product types and demand patterns. Layout optimization principles of positioning high-activity items near key areas apply across industries. Routing algorithms can be calibrated to different warehouse configurations and constraints. Thus while specific numerical results may vary across settings, the analytical framework and improvement approaches should translate effectively to other warehouse environments.

6.4 Limitations and future research directions

Several limitations of this research suggest directions for future investigation. Most critically, all quantitative results derive from a single case study comprising nine customer requisitions selected from one medium-sized warehouse in Portugal. No formal statistical testing was performed: the reported percentages (54%, 66%, 72%, 74%) are point estimates without confidence intervals, p-values, or other measures of uncertainty. They should therefore be read as indicative rather than definitive. This limitation is particularly important when assessing the combined 66% figure, which is lower than the layout-only 72% because it measures a different operational scenario rather than a worse outcome. Larger, multi-site samples with

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appropriate statistical analysis would be required to establish the robustness and boundary conditions of these findings. Future research could employ larger datasets to more rigorously validate algorithm performance and identify factors predicting greatest benefit.

The routing algorithm implemented represents a relatively simple nearest neighbor heuristic. While this approach proved effective and practical, more sophisticated algorithms including genetic algorithms, ant colony optimization, or machine learning approaches might achieve additional improvements. Future research could compare multiple algorithm types in the same warehouse setting to assess benefit-cost tradeoffs considering both solution quality and implementation complexity. Such comparative studies would provide valuable guidance for practitioners selecting optimization approaches.

Long-term sustainability of improvements requires investigation. This study documented initial implementation and early results, but sustained performance over months and years remains to be demonstrated. Changes in product mix, demand patterns, and personnel could erode benefits if not actively managed. Longitudinal research tracking performance over extended periods would identify factors supporting or undermining sustained improvement and inform maintenance practices. Such research could also quantify benefits of periodic re-optimization versus initial optimization.

The study focused primarily on operational efficiency metrics including distance, time, and cost. While these are fundamental, other performance dimensions deserve attention. Order accuracy, customer service quality, employee satisfaction, and workplace safety all potentially benefit from improved warehouse operations but were not systematically measured in this research. Future studies could employ more comprehensive performance frameworks capturing multiple dimensions of warehouse performance to provide fuller understanding of optimization impacts.

Finally, the integration of warehouse optimization with broader supply chain considerations merits investigation. This study treated the warehouse as a relatively isolated system, but warehouse operations interact with procurement, transportation, and customer service processes. Optimization might generate benefits or create challenges in these connected processes. Research examining warehouse optimization from a systems perspective could identify opportunities for coordinated improvements across supply chain functions and potential unintended consequences requiring management attention.

Finally, to situate these logistics findings within broader regional and socio-economic debates, future work should consider how warehouse efficiency gains translate into territorial competitiveness and employment effects – themes addressed by several contributions previously published in the journal.

7. Conclusions and recommendations

This research has demonstrated that systematic analysis and optimization of warehouse operations can yield substantial improvements in efficiency, cost, and service quality. Through comprehensive ABC classification analysis, detailed layout restructuring planning, and nearest neighbor routing algorithm implementation, the study achieved significant documented benefits including 66-72% reduction in picking distances, 47-48% reduction in picking time, and annual cost savings exceeding €4,600 through combined direct and indirect benefits. These improvements were achieved with minimal capital investment, primarily through intelligent reorganization of existing resources and application of analytical approaches accessible to most organizations.

The magnitude of improvements observed demonstrates the penalty of inadequate warehouse planning and the opportunity available through systematic optimization. Many organizations operate warehouses that evolved incrementally over time without comprehensive review of fundamental design decisions. Product positioning often reflects historical accident rather than analytical planning, while picking processes follow tradition rather than optimization. The case study organization exhibited exactly this pattern, with highest-rotation products located in the most distant warehouse areas due to incremental decisions made without overall system consideration. This situation, while problematic, is far from unique and suggests widespread opportunity for similar improvements across many organizations and industries.

The research confirms and extends theoretical understanding of warehouse optimization principles. ABC classification based on rotation frequency provides an effective foundation for product positioning strategy, as established in prior literature. However, this study demonstrates that simple rotation-based classification should be enhanced by considering product complementarity, physical characteristics, and seasonal variations to achieve optimal results. Similarly, nearest neighbor routing algorithms prove effective for practical warehouse applications despite not guaranteeing globally optimal solutions, but performance can be further enhanced by incorporating warehouse-specific constraints and product handling requirements.

Critical to success was the integration of multiple improvement dimensions rather than pursuing isolated optimizations. Layout restructuring and routing algorithm implementation each generated substantial benefits independently, but combined implementation produced synergistic effects exceeding simple addition of individual improvements. This finding reinforces the importance of comprehensive rather than piecemeal approaches to warehouse optimization. Organizations should resist the temptation to pursue only the most obvious or easily implemented improvements, instead developing integrated optimization strategies that address multiple aspects of warehouse operations simultaneously.

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Several recommendations emerge for organizations seeking to improve warehouse operations. First, conduct comprehensive analysis of current operations before implementing changes. Data-driven understanding of product rotation patterns, picking path characteristics, and cost structures enables identification of highest-impact improvement opportunities and provides baseline for measuring results. Second, prioritize improvements based on both magnitude of benefit and ease of implementation. Early successes build organizational confidence and momentum for more challenging changes. Third, engage warehouse operators throughout the process. Their practical knowledge proves invaluable in identifying problems and designing workable solutions, while their support determines implementation success.

Fourth, adopt incremental implementation approaches that allow learning and adjustment. Attempting comprehensive simultaneous changes increases risk and may overwhelm organizational capacity for change absorption. Phased implementation enables course correction based on experience while still delivering measurable benefits relatively quickly. Fifth, establish mechanisms for sustained performance monitoring and periodic re-optimization. Warehouse environments change over time through product mix evolution, demand pattern shifts, and organizational growth. Initial optimization will gradually lose effectiveness without periodic review and adjustment to maintain performance.

Sixth, recognize that sophisticated technology, while potentially valuable, is not prerequisite for substantial improvement. Basic analytical approaches using readily available tools can deliver significant benefits when applied systematically. Organizations should not defer improvement initiatives while awaiting major technology investments, but rather should pursue accessible improvements immediately while planning longer-term technology strategies. This pragmatic approach generates both immediate benefits and organizational learning that informs future investments.

For the telecommunications sector specifically, the study demonstrates that logistics excellence can provide competitive differentiation in markets where products are increasingly commoditized. The ability to rapidly fulfill customer orders while minimizing costs directly supports both customer satisfaction and profitability. As telecommunications infrastructure deployment accelerates with 5G rollout and fiber network expansion, efficient logistics operations become even more critical to support aggressive deployment schedules. Companies that invest in logistics optimization position themselves for competitive advantage in these growing markets.

Looking forward, several trends will likely influence warehouse optimization practices. Increasing adoption of automation technologies including autonomous mobile robots, automated storage and retrieval systems, and robotic picking will transform warehouse operations in many sectors. However, the fundamental principles demonstrated in this research, particularly strategic product positioning and systematic routing, remain relevant even in highly automated environments. Organizations should view automation as enhancing rather than replacing analytical optimization approaches.

Digitalization of warehouse operations through advanced sensors, real-time location systems, and predictive analytics will enable more dynamic optimization responsive to changing conditions. The simple spreadsheet-based tools employed in this study may evolve into sophisticated integrated systems providing continuous optimization rather than periodic manual analysis. However, the transition from current practices to advanced digital systems will occur gradually, and organizations should not wait for perfect solutions but rather should pursue continuous improvement using available capabilities.

In conclusion, this research has demonstrated that warehouse optimization through integrated layout restructuring and routing algorithm implementation can deliver substantial improvements in operational efficiency, cost structure, and service capability within a single medium-sized Portuguese telecommunications warehouse. The results are based on observational data and simulation rather than statistical testing, and the extent to which they generalise to other settings remains to be established. That said, the methodologies employed offer a replicable framework for small to medium-sized logistics operations in comparable settings, and the benefits achieved justify the implementation effort many times over. As competitive pressures intensify and customer expectations rise, logistics excellence becomes increasingly critical to organizational success. Companies that systematically optimize warehouse operations position themselves for sustained competitive advantage, operational resilience, and superior financial performance in dynamic market environments.

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