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Integrated ABC–VED–AHP Framework for Prioritizing Returned Materials in Electricity Transmission Warehouse Management

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ABSTRACT

Returned materials in electricity transmission warehouses may still possess economic value and operational utility, but their accumulation reduces warehouse efficiency and delays asset recovery decisions. This study aims to develop an integrated decision framework for prioritizing returned materials. The proposed framework combines ABC analysis, VED analysis, physical condition assessment, reuse potential evaluation, and the Analytic Hierarchy Process (AHP), and was applied to 580 returned material items with a total replacement value of IDR 256,057,003,073. The results show that operational criticality is the most influential criterion (0.5342), followed by physical condition, economic value, and reuse potential. The consistency ratio (0.0455) indicates reliable expert judgment. The final prioritization classified 397 items as High Priority, 116 as Medium Priority, and 67 as Low Priority. The proposed framework provides an objective and data-driven approach for returned material management, supporting warehouse optimization, dead stock reduction, and improved asset recovery in electricity infrastructure systems.

Keywords: *Material Return*, *Reverse Logistics*, *ABC Analysis*, *VED Analysis*, AHP.

Introduction

Inventory management is a critical component of supply chain and logistics systems because it directly affects service level, operational reliability, and total logistics cost [1], [2]. In electricity infrastructure companies, inventory management becomes more complex because warehouses manage not only new materials but also returned materials from operation, maintenance, and project replacement activities.

Returned materials are ex-operational materials or equipment dismantled from field operations and returned to the warehouse for evaluation regarding reuse, repair, storage, transfer, or disposal. In electricity transmission systems, these materials may include current transformers, circuit breakers, lightning arresters, disconnecting switches, conductors, and other transmission equipment.

The accumulation of returned materials has become a significant issue in PT PLN (Persero) transmission warehouses based on internal warehouse capacity records [3], [4]. Average utilization reached 93.29%, exceeding the recommended operational threshold. Several warehouses operated close to or above capacity, indicating that returned and inactive assets have become a structural warehouse management problem.

Current classification practices generally rely on administrative categories such as standby, damaged, repair, warranty, or disposal proposal. These categories do not simultaneously represent economic value, operational criticality, physical condition, and reuse potential. This study addresses this gap by developing an integrated ABC-VED-AHP framework for returned material prioritization.

Although this study uses PT PLN (Persero) as a case study, the proposed framework is designed to be applicable to other infrastructure-based organizations that manage returned materials, spare parts, and non-moving assets. Therefore, the contribution of this study is not limited to a company-specific solution but also provides a structured prioritization approach for returned material management in utility and infrastructure warehouse systems.

Inventory management aims to ensure material availability while minimizing inventory-related costs. In infrastructure-based industries, inventory management also includes returned materials from maintenance and replacement activities. These materials require specific treatment because their condition, value, and usability are uncertain.

Reverse logistics refers to the movement of materials from the point of use back to the organization for reuse, repair, remanufacturing, recycling, or disposal [5], [6], [7], [8], [9]. In electricity transmission, returned materials are part of reverse logistics because removed equipment is returned to the warehouse for technical and economic evaluation. Effective reverse logistics can improve asset utilization, reduce waste, and support sustainable inventory management.

In addition to improving asset utilization, reverse logistics also contributes to sustainability initiatives by reducing unnecessary procurement, minimizing material waste, and extending asset life cycles. Recent studies have emphasized that integrating environmental considerations into inventory decision-making supports green supply chain management while maintaining operational efficiency [6], [8], [9]. Therefore, sustainability aspects provide an additional perspective for future development of returned material prioritization frameworks.

ABC analysis classifies inventory based on economic value using the Pareto principle [10], [11], [12]. Category A represents high-value materials, Category B represents medium-value materials, and Category C represents low-value materials. The economic value is calculated from replacement cost and quantity.

However, ABC analysis only considers financial value. In electricity infrastructure systems, some low-value materials may still be operationally critical. Therefore, ABC analysis should be complemented with operational criticality assessment.

VED analysis classifies materials based on operational criticality [13], [14]. Vital materials may cause severe operational disruption if unavailable, Essential materials support system performance, and Desirable materials have relatively minor operational impact.

VED analysis is relevant for electricity transmission systems because reliability is a key requirement. Therefore, material prioritization should consider not only economic value but also the impact on system continuity and maintenance readiness.

The Analytic Hierarchy Process is a multi-criteria decision-making method used to determine the relative importance of criteria through pairwise comparisons [15], [16]. AHP evaluates expert judgment consistency using the consistency ratio.

AHP is suitable for returned material prioritization because the decision involves both quantitative and qualitative criteria, including economic value, operational criticality, physical condition, and reuse potential.

Previous studies have applied ABC analysis, VED analysis, and AHP in inventory classification and spare parts management [10], [11], [12], [13]. However, most studies focus on active inventory systems where demand movement and consumption patterns are available. In returned material warehouses, many items are non-moving or dead stock, making movement-based classification less relevant.

Furthermore, limited studies have integrated economic value, operational criticality, physical condition, and reuse potential into a single framework for returned material management in electricity infrastructure systems. Unlike previous studies that mainly focus on demand movement or economic value, this study addresses returned materials whose future usability is uncertain. Therefore, this study proposes an integrated ABC–VED–AHP framework by incorporating physical condition and reuse potential as additional criteria for returned material prioritization.

Research Method

Research Design

This study uses a case-based quantitative and qualitative approach. Quantitative data are used to evaluate economic value and warehouse utilization, while qualitative assessments are used to evaluate operational criticality, physical condition, and reuse potential. The research framework consists of data collection, ABC classification, VED classification, physical condition assessment, reuse potential assessment, AHP weighting, composite scoring, priority categorization, and managerial strategy formulation.

Data Collection

The data consist of secondary and primary data. Secondary data were obtained from the warehouse inventory database, including material identification, material type, warehouse location, quantity, replacement cost, administrative status, and warehouse capacity utilization [3], [4]. Primary data were obtained through physical inspection and expert assessment.

Physical inspection was used to assess structural condition, component completeness, corrosion or degradation level, and technical documentation availability. Expert assessment was used to evaluate operational criticality and reuse potential.

The AHP pairwise comparison involved five experts representing warehouse logistics, transmission maintenance, asset management, transmission operation, and engineering planning functions within PT PLN (Persero). All experts had more than ten years of professional experience in electricity transmission and warehouse management. Their practical expertise ensured that the pairwise comparison reflected actual operational priorities and supported the reliability of the AHP weighting process.

Table 1. Profile of Experts Involved in the AHP Assessment

Expert	Position	Area of Expertise	Experience
Expert 1	Warehouse Logistics Supervisor	Warehouse & Inventory Management	15 years

Expert 2	Transmission Maintenance Engineer	Transmission Asset Maintenance	17 years
Expert 3	Asset Management Engineer	Asset Lifecycle Management	14 years
Expert 4	Transmission Operation Engineer	Power System Operation	16 years
Expert 5	Engineering Planning Engineer	Transmission Planning & Material Management	13 years

The five experts independently performed pairwise comparisons using Saaty's 1–9 fundamental scale. The resulting judgments were aggregated to construct the pairwise comparison matrix, producing a consistency ratio (CR) of 0.0455, which is below the acceptable threshold of 0.10 and indicates a consistent level of expert judgment.

ABC Classification

ABC classification is used to categorize returned materials based on economic value. The economic value of each material is calculated as:

$$\mathrm{EV}_i = RC_i \times Q_i \tag{1}$$

Where:
EV_i is the economic value of material (i),
RC_i is the replacement cost of material (i),
Q_i is the quantity of material (i).

Materials are sorted by economic value and grouped into A, B, and C categories. For composite scoring, the categories are converted into numerical scores as shown in Table 2.

Table 2. ABC Category Score

ABC Category	Interpretation	Score
A	High economic value	3
B	Medium economic value	2
C	Low economic value	1

VED Classification

VED classification evaluates the operational criticality of each material based on its impact on transmission reliability, maintenance execution, and operational safety. The VED categories and scores are shown in Table 3.

Table 3. VED Category Score

VED Category	Interpretation	Score
Vital	Severe operational impact if unavailable	3
Essential	Important but temporary unavailability can be tolerated	2
Desirable	Minor operational impact	1

Physical Condition Assessment

Physical condition assessment evaluates the technical feasibility of returned materials for reuse or repair. Four sub-criteria are used: structural condition, component completeness, corrosion or degradation level, and technical documentation availability, as shown in Table 4.

Table 4. Physical Condition Assessment Criteria

Sub-criterion	Weight	Assessment Focus
Structural condition	40%	Cracks, deformation, broken parts, physical integrity
Component completeness	30%	Availability of main parts and accessories
Corrosion/degradation	20%	Rust, oxidation, insulation aging, surface degradation
Technical documentation	10%	Nameplate, manual, maintenance record, traceability

The physical condition score is then converted into a 1–3 scale for consistency with other criteria:

Table 5. Physical Condition Score Conversion

Physical Condition	Initial Score	Converted Score
Good / Very good	4–5	3
Fair	3	2
Poor / Very poor	1–2	1

Reuse Potential Assessment

Reuse potential measures the feasibility and usefulness of returned materials for future operational use. It is evaluated based on repairability, demand frequency, and market availability.

Table 6. Reuse Potential Assessment Criteria

Sub-criterion	Description	High Score Condition
Repairability	Technical and economic feasibility of repair	Repair cost is relatively low compared to replacement cost
Demand frequency	Historical or expected need for the material	Material is frequently needed for maintenance or replacement
Market availability	Ease of procuring new material	Material is difficult to procure, obsolete, imported, or has long lead time

The reuse potential score is converted into three categories: high reuse potential = 3, medium reuse potential = 2, and low reuse potential = 1.

AHP Weighting

AHP determines the relative importance of economic value, operational criticality, physical condition, and reuse potential. Experts performed pairwise comparisons using Saaty's 1–9 scale [15], [16]. Consistency was evaluated using the consistency ratio (CR), with CR ≤ 0.10 considered acceptable. In this study, $\lambda max = 4.1229$, CI = 0.0410, and CR = 0.0455, indicating consistent expert judgment.

Composite Priority Score

The final priority score is calculated by multiplying each criterion score by its AHP weight:

$$PS_i = (W_1 \times EV_i) + (W_2 \times OC_i) + (W_3 \times PC_i) + (W_4 \times RP_i) \quad (2)$$

Where:
PS_i is the priority score of material (i),
EV_i is the economic value score,
OC_i is the operational criticality score,
PC_i is the physical condition score,
RP_i is the reuse potential score,
W_1, W_2, W_3, W_4 are AHP weights.
The final score is classified into three priority categories:

Table 7. Final Priority Classification and Handling Strategy

Priority Category	Interpretation	General Strategy
High Priority	High value, high criticality, good condition, or high reuse potential	Retain, repair, strategic stock, or transfer to other units
Medium Priority	Moderate value or moderate operational importance	Selective repair, controlled storage, or further evaluation
Low Priority	Low value, low criticality, poor condition, or low reuse potential	Disposal, scrap, or liquidation

Results and Discussion

Warehouse Utilization Analysis

The warehouse utilization data indicate that returned materials have significantly occupied electricity transmission warehouse capacity. The average warehouse utilization reached 93.29%, exceeding the recommended operational threshold. One warehouse experienced overcapacity above 100%, while several others operated close to full capacity. This condition shows that returned material accumulation has become a structural warehouse management issue rather than a temporary storage problem.

Table 8. Warehouse Utilization of Transmission Implementation Units

Warehouse Area	Total Area (m^2)	Used Area (m^2)	Utilization (%)	Dominant Content
UPT Cikupa	4,804	5,451	113.5	Returned/inactive assets
UPT Cilegon	5,484	5,351	97.6	Returned/inactive assets
UPT Durkos	1,000	500	50.0	Returned and spare materials
UPT Pulogadung	8,670	8,218	94.8	Returned/inactive assets
UPT Cawang	5,253	4,754	90.5	Returned/inactive assets
UPT Gandul	6,404	5,220	81.5	Returned and spare materials
Average	**31,615**	**29,494**	**93.29**	**Non-moving materials**

The high utilization level indicates that warehouse space is being consumed by materials whose future use is uncertain. Without a prioritization framework, valuable and critical materials may not be distinguished from low-value and non-critical materials. Therefore, a structured classification system is needed to support handling decisions.

ABC Classification Results

ABC analysis was conducted on 580 returned material items with a total replacement value of IDR 256,057,003,073. The classification results show that 8 items were categorized as A, 457 items as B, and 115 items as C. Category A consists of a small number of materials with very high replacement value, mainly power transformers and other high-value transmission equipment. Although the number of Category A items is relatively small, these materials represent a significant portion of total asset value and therefore require strict managerial control.

Table 9. ABC Classification Results

ABC Category	Number of Items	Percentage of Items	Interpretation
A	8	1.38%	High economic value
B	457	78.79%	Medium economic value
C	115	19.83%	Low economic value
Total	**580**	**100.00%**	

The dominance of Category B indicates that most returned materials have moderate economic value. This condition implies that warehouse decisions cannot rely only on high-value materials because a large number of medium-value materials also contribute to storage burden and asset recovery potential. Category C materials, although economically lower, still need to be evaluated together with operational criticality before disposal decisions are made.

VED Classification Results

VED analysis was used to evaluate the operational criticality of returned materials. The results show that 408 items were classified as Vital, 108 items as Essential, and 64 items as Desirable. This result indicates that most returned materials are operationally important for electricity transmission reliability, even though they are currently stored as returned or inactive materials.

Table 10. VED Classification Results

VED Category	Number of Items	% of Items	Interpretation
Vital	408	70.34%	Severe operational impact if unavailable
Essential	108	18.62%	Important for operational support
Desirable	64	11.03%	Lower operational impact
Total	**580**	**100.00%**	

The high proportion of Vital materials confirms that returned materials should not be treated merely as obsolete or inactive assets. Some returned materials may still play an important role as backup equipment, emergency replacement materials, or candidates for repair and reuse. Therefore, operational criticality must be included in returned material handling decisions.

Integrated ABC-VED Matrix

The ABC–VED matrix combines economic value and operational criticality to provide an initial prioritization map [18], as shown in Table 11.

Table 11. ABC–VED Matrix and Recommended Strategy

Category	Interpretation	Recommended Strategy
A–V	High value and vital	Top priority: retain, inspect, repair if feasible, strategic stock
A–E	High value and essential	High priority: retain with strict control, repair selectively
A–D	High value but desirable	Review for transfer, sale, or value recovery
B–V	Medium value and vital	High priority: retain as strategic backup
B–E	Medium value and essential	Medium priority: selective repair and controlled storage
B–D	Medium value but desirable	Low priority: evaluate for disposal if condition is poor
C–V	Low value but vital	Medium priority: retain minimum stock due to operational importance
C–E	Low value and essential	Low priority: retain limited quantity or replace if damaged
C–D	Low value and desirable	Disposal priority: scrap or remove from warehouse

The ABC–VED matrix helps identify materials that should be prioritized for retention and repair, as well as materials that should be considered for disposal. The integrated ABC–VED results show that the largest group is

B–V with 360 items, followed by B–E with 97 items, C–D with 64 items, C–V with 40 items, C–E with 11 items, and A–V with 8 items.

Table 12. Integrated ABC–VED Classification Results

ABC–VED Category	Number of Items	% of Items	Main Interpretation
A–V	8	1.38%	High value and vital
B–V	360	62.07%	Medium value and vital
B–E	97	16.72%	Medium value and essential
C–V	40	6.90%	Low value but vital
C–E	11	1.90%	Low value and essential
C–D	64	11.03%	Low value and desirable
Total	**580**	**100.00%**	

This indicates that many medium-value materials remain operationally critical, so physical condition, reuse potential, and AHP weighting are needed for final prioritization.

AHP-Based Criteria Weighting

AHP is used to determine the relative importance of economic value, operational criticality, physical condition, and reuse potential. In electricity transmission warehouse management, operational criticality is expected to receive a high weight because system reliability is a primary concern. Economic value is also important because returned materials represent company assets. Physical condition and reuse potential are needed to determine whether materials are technically and economically feasible to retain or repair.

Based on the AHP calculation, operational criticality obtained the highest weight, followed by physical condition, economic value, and reuse potential. This result indicates that returned material handling should prioritize operational continuity while still considering physical feasibility, asset value, and reuse potential. The consistency ratio was checked to ensure that expert judgments were logically consistent.

Table 13. AHP Criteria Weight Results

Criterion	Weight	Rank
Operational Criticality (VED)	0.5342	1
Physical Condition	0.2286	2
Economic Value (ABC)	0.1646	3
Reuse Potential	0.0727	4

The consistency test produced $\lambda max = 4.1229$, CI = 0.0410, and CR = 0.0455. Since $CR < 0.10$, the expert judgment is considered consistent. This result indicates that returned material handling decisions in electricity transmission warehouses are primarily driven by operational reliability considerations, while economic value, physical feasibility, and reuse potential serve as supporting criteria.

Sensitivity Analysis

To evaluate the robustness of the proposed framework, a simple sensitivity analysis was conducted by varying the weight of the operational criticality criterion while proportionally adjusting the remaining criteria. The analysis showed that moderate changes in criterion weights did not significantly alter the overall priority classification. High-priority materials remained dominated by power transformers and current transformers because these materials consistently exhibited high operational importance and acceptable physical conditions. This finding indicates that the proposed framework is relatively stable against reasonable variations in expert judgment.

Nevertheless, larger changes in criterion weights may influence the ranking of materials with similar composite scores. Therefore, future studies should investigate broader sensitivity scenarios and probabilistic weighting approaches to further validate the robustness of the framework.

Table 14. Sensitivity Analysis under Different Operational Criticality Weight Scenarios

Scenario	Economic Value	Operational Criticality	Physical Condition	Reuse Potential	High Priority	Medium Priority	Low Priority
Original	0.1646	0.5342	0.2286	0.0727	397	116	67
OC −10%	0.1834	0.4807	0.2548	0.0810	397	116	67
OC +10%	0.1457	0.5876	0.2023	0.0644	397	116	67
OC −20%	0.2023	0.4273	0.2810	0.0894	389	124	67
OC +20%	0.1268	0.6410	0.1761	0.0560	408	108	64

A sensitivity analysis was conducted by varying the weight of the most influential criterion, Operational Criticality, by ±10% and ±20%, while proportionally adjusting the remaining criteria to maintain a total weight of one. As shown in Table 14, no changes in the priority classification were observed under the ±10% scenarios, indicating that the proposed framework is robust against moderate variations in expert judgment. When the Operational Criticality weight was varied by ±20%, small changes in the number of materials within each priority category were observed. Specifically, decreasing the weight by 20% reduced the number of High Priority materials from 397 to 389 and increased Medium Priority materials from 116 to 124, whereas increasing the weight by 20% increased High Priority materials to 408 and reduced Medium Priority materials to 108. The number of Low Priority materials changed only slightly (67 to 64). These results demonstrate that the proposed ABC–VED–AHP framework is stable under moderate changes and only exhibits limited sensitivity under more substantial variations in criterion weights.

Proposed Warehouse Decision Support System Architecture

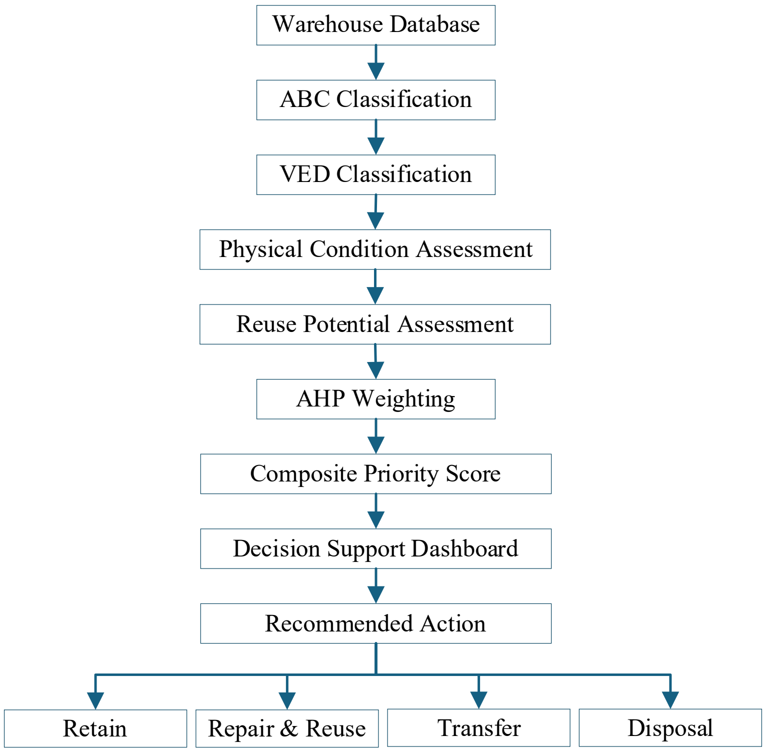

Figure 1. Proposed Warehouse Decision Support System Architecture Based on the ABC–VED–AHP Framework

Figure 1 illustrates the conceptual architecture of a warehouse decision support system developed from the proposed ABC–VED–AHP framework. Material information stored in the warehouse database is processed sequentially through ABC classification, VED classification, physical condition assessment, and reuse potential assessment. The AHP weighting method integrates these criteria to calculate a composite priority score for each returned material. The resulting priority information is presented through a decision support dashboard that recommends appropriate managerial actions, including retention, repair and reuse, transfer, or disposal. Although the proposed architecture was not implemented as a software application in this study, it provides a practical framework for future digitalization of warehouse material management within PT PLN (Persero).

Composite Priority Classification

The composite priority score integrates economic value, operational criticality, physical condition, and reuse potential into a single score. The results show that 397 items were classified as High Priority, 116 items as Medium Priority, and 67 items as Low Priority.

Table 15. Final Priority Classification Results

Priority Category	Number of Items	Percentage of Items	Recommended Strategy
High Priority	397	68.45%	Retain
Medium Priority	116	20.00%	Repair & Reuse
Low Priority	67	11.55%	Disposal
Total	**580**	**100.00%**	

The high proportion of High Priority materials indicates that many returned materials should not be immediately disposed of because they still have operational importance, economic value, acceptable physical condition, or high reuse potential. These materials should be retained as strategic stock or evaluated for transfer to other units that require them. Medium Priority materials should be evaluated for repair and reuse, while Low Priority materials should be prioritized for disposal, scrap, or liquidation to reduce warehouse burden.

The physical condition assessment shows that 32 items were categorized as Very Good, 24 items as Good, 412 items as Fair, and 112 items as Poor. Reuse potential assessment shows that 408 items have High reuse potential, 75 items have Medium reuse potential, and 97 items have Low reuse potential. These findings support differentiated handling strategies rather than uniform disposal treatment.

The highest-priority materials were dominated by power transformers and current transformers because these materials have high operational criticality, high economic value, and relatively good physical condition. Therefore, these materials should be retained as strategic assets and evaluated for reuse or transfer to units that require them.

Table 16. Physical Condition and Reuse Potential Assessment Results

Assessment Aspect	Category	Number of Items	Percentage of Items
Physical condition	Very Good	32	5.52%
Physical condition	Good	24	4.14%
Physical condition	Fair	412	71.03%
Physical condition	Poor	112	19.31%
Reuse potential	High	408	70.34%
Reuse potential	Medium	75	12.93%
Reuse potential	Low	97	16.72%

Managerial Implication

The proposed framework supports objective returned material decisions by integrating economic value, operational criticality, physical condition, and reuse potential into a single scoring system. It helps managers determine whether materials should be retained, repaired, transferred, or disposed of, while supporting warehouse capacity optimization, dead stock reduction, asset recovery, and future integration into digital warehouse systems [17].

System Implementation Perspective

The proposed framework can be integrated into a warehouse information system to support automated decision-making [17], [18]. Inventory data, physical inspection results, and expert assessments can be processed through the ABC–VED–AHP framework to generate composite priority scores. The resulting recommendations may trigger appropriate warehouse handling procedures such as retention, repair, transfer, or disposal. Such integration would improve decision consistency, reduce manual evaluation effort, and support digital warehouse transformation.

Conclusion

This study proposes an integrated ABC–VED–AHP framework for prioritizing returned materials in electricity transmission warehouse management. The framework combines economic value, operational criticality, physical condition, and reuse potential into a composite priority score to support more objective and data-driven handling decisions.

The framework classifies returned materials into high, medium, and low priority categories. High-priority materials should be retained, repaired, or transferred for operational reuse; medium-priority materials require selective repair and further evaluation; and low-priority materials should be considered for disposal, scrap, or liquidation. Compared with previous inventory classification studies, this research contributes by integrating physical condition and reuse potential into returned material prioritization, particularly for non-moving and dead stock items in infrastructure warehouse systems.

Future studies should validate the framework using larger datasets from different infrastructure sectors such as railway, telecommunication, and water utility systems to evaluate its general applicability. Machine learning algorithms may also be integrated with historical warehouse decisions to automate priority prediction [11]. Furthermore, future research should investigate sensitivity analysis under broader weighting scenarios, compare AHP with other multi-criteria decision-making methods such as TOPSIS and PROMETHEE [10], [12], incorporate cost-benefit analysis and sustainability indicators [8], [9], and integrate computer vision techniques for automated physical condition assessment. In addition, future research may develop a fully automated warehouse decision support system by integrating the proposed framework with enterprise warehouse management systems and realtime inventory databases [17].

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