Spektrum Industri
Vol. 24, No. 2, 2026, pp. 396–405
ISSN (print) 1693-6590 | ISSN (online) 2442-2630
https://journal3.uad.ac.id/index.php/spektrum/index

Assessing Technological Sophistication of Energy Distribution Warehouses Using a Technometric Framework

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ARTICLE INFO

Article history
Received March 27, 2026
Revised July 10, 2026
Accepted July 21, 2026

Keywords
Technometric;
Technology contribution Coefficient (TCC);
Warehouse energy Distribution;
Warehouse technology.

ABSTRACT

Warehousing plays a critical role in energy distribution systems, where operational reliability depends on technological sophistication. However, structured and quantitative approaches for assessing technological capability in energy distribution warehouses remain limited. This study aims to evaluate the technological sophistication of a real-world energy distribution warehouse using a technometric-based measurement instrument. The novelty of this research lies in the empirical application of a specialized technometric instrument for multidimensional warehouse technology assessment. A quantitative case study approach was employed using five assessment components: warehouse facility, warehouse operation, warehouse maintenance, warehouse product, and warehouse human and organization. Technological sophistication was evaluated using State of the Art (SOTA), component contribution, and Technology Contribution Coefficient (TCC) analyses. The results showed a TCC value of 0.456, indicating a semi-modern level of technological sophistication. The findings reveal an imbalance in technological development across warehouse components and identify priority areas for improvement. This study demonstrates the usefulness of technometric assessment in supporting technology development and modernization planning in energy distribution warehouses.

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1. Introduction

Warehouses play a critical role in ensuring the continuity, reliability, and responsiveness of modern supply chains (Zhang et al., 2023). In the energy sector, distribution warehouses are not merely storage facilities but strategic assets that support maintenance activities, emergency response, and the availability of critical equipment required to maintain uninterrupted electricity distribution services (Kisanjani et al., 2026; Utama & Salsabilah, 2025). Consequently, the technological capability of warehouses has become increasingly important, as warehouse performance directly influences operational reliability and service quality throughout the energy distribution network (International Energy Agency, 2020). To improve warehouse performance, organizations have increasingly adopted digital technologies such as Warehouse Management Systems (WMS), Internet of Things (IoT), data analytics, and automation technologies (Ben-Daya et al., 2019; Strøm et al., 2025).

These developments have transformed conventional warehouse into more intelligent and interconnected systems capable of enhancing inventory accuracy, operational, efficiency, and service responsiveness (Esmaeilion et al., 2025; Piratelo et al., 2021; Ribeiro et al., 2022; Tubis & Rohman, 2023; Winkelhaus & Grosse, 2020; Zhang et al., 2023). As warehouse technologies continue to evolve, organizations require systematic approaches to assess the sophistication level of their technological systems and identify priorities for future technological development. However, existing studies primarily evaluate warehouses from specific perspectives rather than assessing technological sophistication as an integrated system. Previous research has focused on operational performance optimization, warehouse automation, energy efficiency, simulation-based decision support, and artificial intelligence applications in logistics (Ali & Kaur, 2022; Ellithy et al., 2024; Le et al., 2023; Liu et al., 2024; Lu et al., 2024; Tiwari, 2023). While these approaches provide valuable insights for improving particular warehouse functions, they generally evaluate isolated dimensions of warehouse systems. As a result, they are unable to comprehensively capture the combined contributions of physical facilities, operational processes, maintenance practices, information systems, and organizational capabilities that collectively determine warehouse technological sophistication.

This limitation reveals an important research gap. As highlighted by Tikwayo & Mathaba (2023), warehouse technology has advanced significantly. However, there remains a lack of quantitative and multidimensional frameworks capable of evaluating technological sophistication in a holistic manner, particularly for energy distribution warehouses. Existing evaluation approaches tend to rely on performance indicators, maturity assessments, or technology specific analyses, which provide only partial representations of warehouse technological capability (Facchini et al., 2019; Zoubek & Simon, 2021). Consequently, decision makers often lack a structured basis for identifying technological strengths, weaknesses, and development priorities across multiple warehouse components. Furthermore, no existing approach provides a structured quantitative framework capable of simultaneously evaluating facility, operation, maintenance, product, and human organizational dimensions within a single assessment model.

To address this gap, a technometric based-measurement instrument has been previously developed to evaluate the level of technological sophistication in energy distribution warehouses. The instrument integrates five main components, namely warehouse facility, warehouse operation, warehouse maintenance, warehouse product, and warehouse human and organization, and is designed to measure degree of sophistication, state of the art, and Technology Contribution Coefficient (TCC) in a structured manner (Sharif, 1994). Although the instrument provides a comprehensive conceptual framework, it has not yet been empirically applied to real world warehouse systems. Consequently, its practical applicability, sensitivity in distinguishing technological levels, and ability to generate meaningful decision support insights remain unverified.

Accordingly, this study applies the technometric-based measurement instrument to a real-world case study in an electricity distribution company in Indonesia. The study evaluates the technological sophistication level of the warehouse through the assessment of degree of sophistication, state of the art values, component contributions, and TCC calculations (Sharif et al., 1987). Furthermore, simulation scenarios are conducted to analyze the potential impact of technological improvement initiatives on overall warehouse technological performance. The novelty of this research lies in the first empirical implementation of a specialized technometric instrument developed specifically for energy distribution warehouses. While previous studies have primarily focused on evaluating individual aspects of warehouse systems, such as automation, operational performance, energy efficiency, or logistics optimization, this study applies a multidimensional measurement framework that simultaneously evaluates warehouse facility, operation, maintenance, product, and human organizational dimensions within a single assessment system (Boysen et al., 2019).

Furthermore, this research extends the application of the instrument beyond measurement by incorporating simulation-based improvement scenarios to evaluate the potential impact of technological development initiatives on the overall Technology Contribution Coefficient (TCC). This enables the framework not only to assess the current level of technological sophistication but

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also to support future technology planning and modernization decisions. The contributions of this research are threefold. First, it provides empirical validation of a technometric-based instrument for measuring technological sophistication in energy distribution warehouses. Second, it demonstrates a structured approach for assessing and comparing technological capability across multiple warehouse components. Third, it offers practical decision support insights for planning technology development and modernization strategies within electricity distribution warehouse operations.

2. Method

2.1. Research Design

This study employs an applied quantitative research approach using a case study strategy. The objective of the study was to implement and evaluate a previously developed technometric based instrument for measuring the technological sophistication of an energy distribution warehouse. The case study was conducted in an electricity distribution company in Indonesia. The assessment involved three experts selected through purposive sampling, consisting of a Logistics Team Leader, a Warehouse Manager, and a Warehouse Administrator. These experts were selected based on their direct involvement in warehouse operations and technology implementation. Expert judgment was employed to assess the technological sophistication indicators because the evaluation requires contextual knowledge of warehouse technologies and operational practices.

2.2. Measurement Framework

The measurement framework applied in this study is based on the technometric approach, which evaluates technology as an integrated system composed of multiple components. The instrument consists of five main components: warehouse facility, warehouse operation, warehouse maintenance, warehouse product, and warehouse people and organization. Each component is further decomposed into several subcomponents and measurable indicators that represent the degree of technology implementation. The framework in Fig. 1, enables a structured and quantitative assessment of technological sophistication through three dimensions: degree of sophistication, state of the art, and technology contribution.

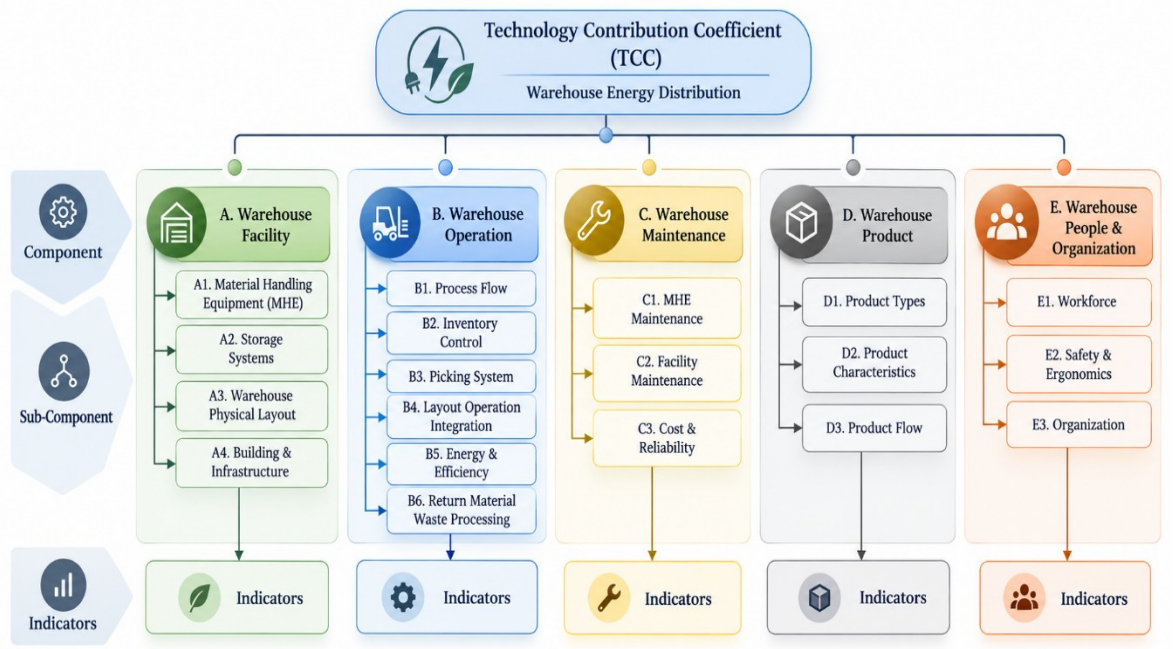


Fig. 1. Five main component energy distribution Warehouse

The measurement instrument was adopted from a previously developed framework and had been validated through expert review during the instrument development stage.

2.3. Measurement Procedure

The measurement procedure consists of several sequential stages to ensure a systematic and quantitative evaluation of technological sophistication in the warehouse system.

2.3.1. Indicator Scoring

Each indicator was evaluated based on predefined technological sophistication, reflecting the actual implementation of technology in warehouse operations. The assessment uses predefined technological anchor levels developed during the instrument design stage. This scoring process captures the relative advancement level of each indicator and serves as the initial step in quantifying technological conditions. The final score for each indicator is determined based on expert consensus.

2.3.2. Normalization

Indicator scores were normalized to a 0-1 scale to ensure comparability across components. The normalized values represent the relative technological position of each indicator.

2.3.3. State of the Art (SOTA) Calculation

The State of the Art (SOTA) value is calculated as the average of the normalized score of each warehouse component, representing its technological advancement Haines & Sharif (2006) in Eq. (1).

$$SF_i = \frac{1}{10}\left[\frac{\Sigma_k t_{ik}}{ki}\right] k = 1,2,\ldots,\ldots,k_i \quad (1)$$

SF_i = state of the art of the warehouse facility component (F) for the item − i
t_{ik} = state of the art value of the item − i criterion − k
k_i = number of warehouse facility
i = item measured; i = 1,2,3,..,n

2.3.4. Component Contribution

The contribution of each component represents its relative role in determining the overall level of technological sophistication within the warehouse system. This contribution is calculated by integrating the State of the Art (SOTA) value with the predefined lower and upper limits of technological sophistication for each component. The lower limit reflects the minimum level of technological capability, while the upper limit represents the maximum achievable level within the system. These limits were established during the instrument development stage based on technological anchor levels and expert review. The calculation of component contribution is intended to capture how far each component has progressed within its potential technological range. By incorporating both the SOTA value and the technological limits, this approach provides a more realistic representation of the contribution of each component to the overall system performance. The component contribution is calculated using the following equation Sukma et al. (2023) in Eq. (2).

$$F = 1/9[LF + SF(UF - LF)] \quad (2)$$

LF = Lower limit warehouse facility
UF = Upper limit of warehouse facility
SF = SOTA warehouse facility

In addition, the intensity of component contribution is represented by weighting factors, denoted as $\beta_f, \beta_o, \beta_m, \beta_p, \beta_h$, which correspond to the normalized weights of each technology component. These weights reflect the relative importance of each component within the overall system and are obtained through a pairwise comparison process. The pairwise comparison results were derived from expert judgments obtained during the instrument development stage. To ensure the reliability of the weighting process, a consistency ratio (CR) is used as a parameter to evaluate whether the judgments

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made during the pairwise comparison are consistent. The criteria for consistency are defined as follows (Atikah, 2020).

$CR \leq 0.1$ = consistent
$0.1 < CR \leq 0.15$ = moderately consistent
$CR > 0.15$ = inconsistent

The use of the consistency ratio ensures that the weighting results are valid and can be used in further calculations. Furthermore, the Technology Contribution Coefficient (TCC) is understood as an aggregate indicator that reflects the relative contribution of technological components within a system. In this study, TCC is used as the primary basis for evaluating the level of technological sophistication of the warehouse.

2.3.5. Technology Contribution Coefficient (TCC)

The overall technological sophistication of the warehouse system was measured using the Technology Contribution Coefficient (TCC) in Eq. (3), which integrates the contribution of all technological components and their weighting factors (Sukma et al., 2023).

$$TCC = F^{\beta f} \times O^{\beta o} \times M^{\beta m} \times P^{\beta p} \times H^{\beta h} \quad (3)$$

Where:
TCC = Technology Contribution Coefficient
F, O, M, P, H = contribution of component
β_f = weight of component f
m = total number of components

The weighting factors were adopted from the previously developed and validated instrument Sukma et al. (2023) and were treated as fixed parameters in the TCC calculation. The resulting weighting factors for each component are presented as follows in Table 1.

Table 1. Weighting factors

Component	Weight	Percentage
Warehouse Facility	0.108	10.8%
Warehouse Operation	0.427	42.7%
Warehouse Maintenance	0.270	27.0%
Warehouse Product	0.052	5.2%
Warehouse Human & Organization	0.142	14.2%

To ensure the reliability of the weighting process, a consistency test was conducted. The results are as follows.

$$\lambda_{\max} = 5.264$$
Consistency Index (CI) = 0.066
Random Index (RI) = 1.12 (for $n = 5$)
Consistency Ratio (CR) = 0.059

Since the obtained consistency ratio satisfies the condition $CR < 0.10$, the pairwise comparison results are considered consistent and methodologically acceptable. This indicates that the expert judgments used to determine the weighting factors are reliable. Furthermore, the TCC serves as the primary indicator for assessing the level of technological sophistication in the energy distribution warehouse. The calculated TCC value is subsequently used as the basis for evaluating and classifying

the technological level of the warehouse system. To facilitate interpretation, the TCC value can be categorized into the following levels (Sukma et al., 2023).

a) $0.0 \leq TCC \leq 0.3$: Low (traditional)
b) $0.3 < TCC \leq 0.5$: Semi modern
c) $0.5 < TCC \leq 0.7$: Modern
d) $0.7 < TCC \leq 1.0$: Advanced

3. Results and Discussion

3.1. Component Contribution Calculation

Based on the measurement results, the technological sophistication of the warehouse system was evaluated using the State of the Art (SOTA), component contribution, and Technology Contribution Coefficient (TCC). Using the SOTA values and the lower and upper limits, the contribution of each component is calculated as follows Table 2.

Table 2. Result Contribution Calculation

Component	Lower	Upper	SOTA	Contribution
Warehouse Facility	1	6	0.5	0.389
Warehouse Operation	1	6	0.6	0.444
Warehouse Maintenance	1	6	0.5	0.389
Warehouse Product	2	6	0.6	0.489
Warehouse Human & Organization	1	8	0.8	0.733

TCC Calculation, using the predefined weighting factors Table 1, the TCC value is calculated using in Eq. (4) and Eq. (5).

$$TCC = F^{0.108} \times O^{0.427} \times M^{0.270} \times P^{0.052} \times H^{0.142} \quad (4)$$

$$TCC = 0.389^{0.108} \times 0.444^{0.427} \times 0.389^{0.270} \times 0.489^{0.052} \times 0.733^{0.142} \quad (5)$$

$$TCC = 0.456$$

3.2. Component Analysis

The component contribution results indicate varying levels of technological sophistication across the warehouse system. Warehouse Human & Organization achieved the highest contribution value (0.733), reflecting strong human capabilities, organizational support, and managerial readiness. This suggests that the warehouse has a solid foundation for future technology adoption. In contrast, Warehouse Facility recorded a relatively low contribution value (0.389), indicating that infrastructure and supporting facilities have not been modernized to the same extent as organizational capabilities. Such limitations may reduce operational efficiency and hinder the implementation of more advanced warehouse technologies.

Similarly, Warehouse Maintenance also obtained a low contribution value (0.389), suggesting that maintenance activities remain largely conventional and have not fully utilized technology-based maintenance approaches. Warehouse Operation (0.444) and Warehouse Product (0.489) showed moderate contribution levels, indicating partial technology adoption but with room for further integration. Although Warehouse Operation received the highest weighting factor, its contribution remains moderate, highlighting its importance as a priority area for technological improvement. Overall, the results suggest that technology adoption remains uneven across warehouse components, which may limit the achievement of higher technological sophistication. The variation in component contribution values indicates that technological development has not progressed uniformly across all warehouse dimensions. This finding is consistent with previous studies showing that warehouse modernization often occurs incrementally according to operational priorities and resource allocation (Gu et al., 2007). From a technometric perspective, balanced development across components is

essential because weaknesses in one component may constrain overall system performance (Sharif, 2012; Sharif et al., 1987; Sharif, 1994; Sharif & Ramanathan, 1991).

3.3. Radar Chart Analysis of Component Contribution

The radar chart illustrates the distribution of component contributions (C_f) across the five main dimensions of the warehouse system.

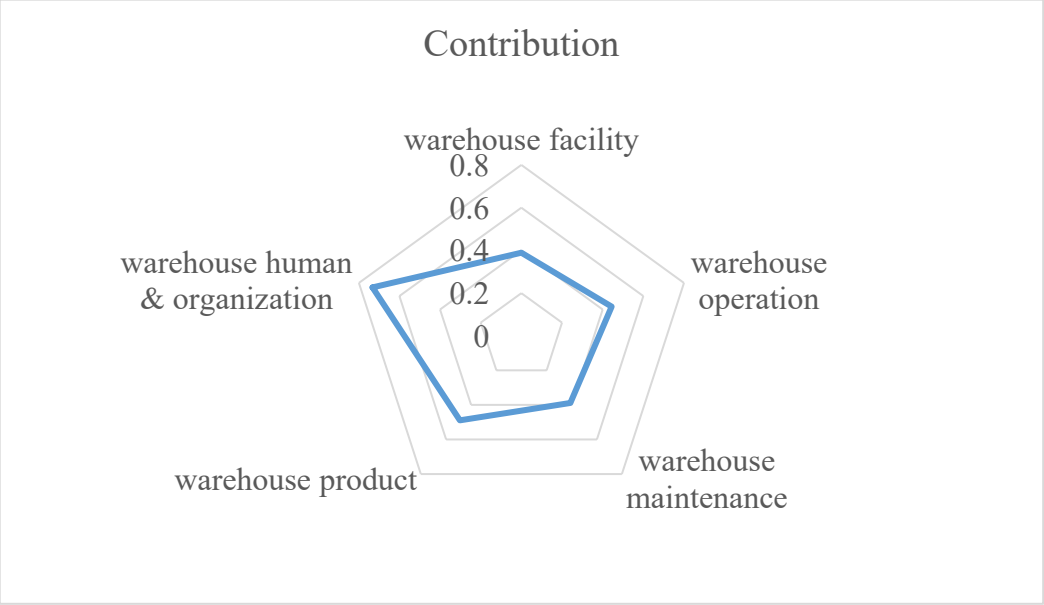


Fig. 2. Radar Chart Analysis

Fig. 2 shows an imbalanced technological profile across the warehouse components. Warehouse Human & Organization forms the strongest dimension, while Warehouse Facility and Warehouse Maintenance represent the weakest areas. This imbalance suggests that organizational readiness has advanced more rapidly than supporting infrastructure and maintenance systems. According to the technometric perspective, such disparities may limit overall system integration and reduce the effectiveness of technology implementation. Therefore, future improvement efforts should prioritize facility and maintenance development to achieve a more balanced technological profile. This imbalance indicates that technological development is concentrated in certain components, while weaker components may constrain the effectiveness of stronger components and reduce overall system integration (Boysen et al., 2019).

The TCC value of 0.456 categorizes the warehouse as semi modern, indicating that technological adoption has progressed beyond traditional practices but has not yet reached a fully integrated level. The results demonstrate that overall technological sophistication is strongly influenced by the moderate performance of Warehouse Operation and Warehouse Maintenance, which possess relatively high weighting factors in the technometric model (Ben-Daya et al., 2019). Consequently, improvements in these components are expected to generate the greatest impact on increasing the overall TCC value. These findings support the technometric perspective that technological performance depends on the interaction among multiple components rather than on a single dimension (M. N. Sharif et al., 1987). Similar findings have been reported in previous studies, where organizational readiness often develops faster than infrastructure modernization because of differences in investment priorities and implementation complexity (Gu et al., 2007; Tubis & Rohman, 2023; Winkelhaus & Grosse, 2020). For energy distribution warehouse, strengthening facility, maintenance, and operational technologies is essential to improve responsiveness and service continuity while reducing technological imbalances across warehouse components (Karunarathna et al., 2020).

4. Conclusion

This study developed and applied a technometric-based measurement framework to evaluate the technological sophistication of an energy distribution warehouse. The results show that the overall Technology Contribution Coefficient (TCC) is 0.456, indicating that the warehouse is at a semi-modern level of technological development. The findings show that Warehouse Human & Organization provides the strongest technological contribution, while Warehouse Facility and Warehouse Maintenance require further improvement. The novelty of this study lies in the development of a technometric-based measurement framework specifically adapted for energy distribution warehouses by integrating warehouse specific technological components into a structured evaluation instrument. The proposed framework provides a systematic approach for identifying technology gaps and supporting warehouse modernization planning. This study was limited to a single case study and relied partly on expert judgment, which may affect the generalizability of the findings. Future research should validate the proposed framework across multiple warehouse enviroments and incorporate objective operational performance data to further improve the robustness and applicability of the assessment framework.

Author Contribution: Putri Khosuma and Alva Edy Tontowi conceived the research and designed the methodology. Putri Khosuma conducted the literature review, developed the instrument, collected and analyzed the data, and drafted the manuscript. Alva Edy Tontowi supervised the research, reviewed the manuscript, and approved the final version.

Funding: This research received no external funding.

Acknowledgment: The authors thank the Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, and all experts and respondents for their valuable contributions.

Conflicts of Interest: The authors declare no conflict of interest.

Declaration of AI-Tool Usage: AI-assisted tools were used to support manuscript proofreading, verify the consistency of variables and mathematical notation, and check reference formatting. All outputs were reviewed and verified by the authors, who take full responsibility for the accuracy and integrity of the final manuscript.

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