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Research paper

A Novel Hybrid Conceptual MCDM Model to Assess and Rank The Performance of Cold Storage Service Providers

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Abstract

Cold Chains (CCs) furnish a regulated environment for the storage, transportation, and distribution of temperature sensitive products. Cold Storage Service Providers (CSSPs) act as intermediaries within the food processing value chain by preserving the quality of a wide range of foods. Further, Cold Chain Performance (CCP) is crucial towards maintaining quality, safety, and economic value of the foods. Consequently, several research studies focused on formulating Multi-Criteria Decision-Making (MCDM) models to enhance CCP. Nevertheless, the focus of such studies was on enhancing performance within specific dimensions viz., sustainability, traceability, digitalization, or resilience etc. Accordingly, this study aims at addressing the research gap, by formulating a novel hybrid conceptual MCDM model integrating Fuzzy Analytical Network Process (FANP) and MultiAtributive Ideal-Real Comparative Analysis (MAIRCA) to holistically assess and rank the performance of CSSPs across multiple performance dimensions.

Keywords: *CCs; CSSPs; CCP; FANP; MAIRCA; MCDM.*

1. Introduction

The post-harvest management of foods, until they reach the final customer is facilitated through Cold Chains, a special form of Supply Chains that are well-equipped to handle environmentally sensitive products within controlled environments. Additionally, global food losses account for about 25 to 50% of production volumes, in this regard cold chains play a predominant role in curbing the post-harvest losses (quantifiable loss within products quality and quantity), through regulating the atmospheric conditions across all stages of the supply chain from harvesting to consumption (Friedman-Heiman and Miller, 2024; Kitinoja, 2013). Besides, the CCs provide the right environments to slow down food ripening and reduce browning, as well as the loss of nutrients, texture, and flavour, by lowering respiration, lowering ethylene production, lowering water loss and shrivelling, increasing product resistance to ethylene action, and lowering microorganic activities (Kitinoja, 2013). Likewise, the cold chains also foster the achievement of United Nations' Sustainable Development Goals 2 and 12 of achieving food security and enhanced nutrition, by reducing the post-harvest losses through provision of rightful environments towards sustaining the quality and availability of foods for safe human consumption (Rabbi et al., 2021). Consequently, the performance of Cold Chains stands crucial towards ensuring food security across the globe and achieving the United Nations' Sustainable Development Goals 2 and 12.

Thus, multi-dimensional performance improvements foster CCs, to sustain the quality, safety, and economic value of the foods efficiently and effectively. Within this context, MCDM could be useful, as cold chains need to be evaluated holistically for performance involving multiple criteria. Further, MCDM offers several algorithms to help formulate a holistic framework involving multiple criteria for performance assessment and ranking. Likewise, MCDM also facilitates integration of multiple algorithms, by allowing the decision-makers to solve a problem with several conflicting criteria, while also allowing them to express their ambiguous views within the uncertain decision-making environment (Abdulla and Baryannis, 2024, Alastal et al., 2025, Fauadi et al., 2024, and Kumar and Pamucar, 2025). Equally, it also convenes performance benchmarking of service facilities based on multiple criteria, which are often contrary in nature (Uyen et al., 2024).

In this pursuit, several studies concentrated on using MCDM models for performance enhancement and assessment within cold chains, considering their abilities towards handling the intricacies present within the decision-making procedures involving numerous objectives, criteria, and stakeholders (Sahoo and Goswami, 2023). Namely, Liu et al. (2019) formulated a novel MCDM fuzzy decision-making tool integrating triangular fuzzy numbers (TFN), AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) for assessing sustainable performance in accordance with the Triple Bottom Line (TBL) framework. Similarly, Kumar et al. (2022) created a fuzzy AHP and Fuzzy TOPSIS based sustainability assessment framework integrating the triple bottom line (TBL) and circular economy practices. Likewise, Liao et al. (2023) employed a hybrid analytic hierarchy process-fuzzy technique for order preference by similarity to ideal solution (AHP-Fuzzy TOPSIS) decision framework to methodically investigate how best practices affect fresh food CSCs' sustainability performance. Additionally, Kabir et al. (2025) deployed MCDM models to assess the impact of digital

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transformation-related criteria—such as IoT-enabled temperature control, blockchain-based traceability, and smart monitoring towards mapping of the cold chain process and performance enhancement.

Moreover, Mor et al. (2018) leveraged on Interpretive Structural Modelling to analyze the interactions between KPI's (effective information technology, brand management, responsiveness in shipments, accuracy/control over the wastes, effective traceability systems, cold chain infra, quality management, and support for techno innovation) within a dairy supply chain. Besides, Kumar and Choube (2023) developed a sustainability assessment framework for an Indian Dairy Chain using an integrated MCDM technique encompassing Fuzzy AHP and Fuzzy VIKOR (VIseKriterijumska Optimizacija Kompromisno).

However, the scope of the research studies discussed focused on addressing a specific performance dimension of a cold chain (Gurrala and Gonela, 2025). Thus, the current study aims to fill in the research gap of holistic performance assessment and improvement, through the formulation of a novel hybrid MCDM model integrating Fuzzy Analytical Network Process (FANP) and MultiAtributive Ideal-Real Comparative Analysis (MAIRCA), to holistically assess and rank the performance of Cold Storage Service Provider (CSSP) in specific, across multiple dimensions. Taking into consideration that CSSP stands out as the most predominant component of CCs, appearing in a wide variety of sizes and locations, accommodated with a distinct catalog of temperature-controlling devices within a network of interconnected refrigerated buildings, aimed at safeguarding the quality of a wide range of foods, as they wait for the consequent processes or operations within the food chain.

Subsequently, the main contributions of this study to the cold chain literature include:

- Identification of a comprehensive list of criteria for assessment of CSSPs' performance with respect to dimensions drawn from the integration of Balance Score Card (BSC), Service Quality (SERVQUAL), Triple Bottom Line (TBL) Model, and from the literature.
- Finalization of a set of criteria for performance evaluation using focus group studies involving experts from the field and academia, based on decision makers' requirements about developing a reliable, practical, and realistic methodological framework.
- Formulation of an MCDM approach integrating FANP and MAIRCA, offering a novel performance analysis procedure and a thorough assessment methodology that could be utilised as a mathematical tool to assess a CSSP's overall performance.

Subsequently, the article is organized into seven sections. Section 2 provides a glimpse into the literature, highlighting the underpinning theories and insights from focus group discussions towards identifying a comprehensive list of criteria for assessing CSSPs' overall performance. Section 3 introduces the proposed framework integrating FANP and MAIRCA methods. Section 4 concentrates on deriving the local and global criteria weights using ANP based on pair-wise comparisons drawn from the experts (Kazançoğlu et al., 2021). Section 5 details the survey questionnaire used to generate a holistic performance score for a CSSP (Appendix I). Section 6 highlights the application of the proposed framework for benchmarking the performance of a set of CSSPs, based on synthetic data generated for each of the criteria and sub-criterion using the survey questionnaire (Ali et al., 2024; Alrashoud et al., 2015). Section 7 outlines the conclusions and potential directions for future research.

2. Underpinning theories, related literature, and insights from focus groups

2.1. Underpinning theories

The research foundations are drawn from BSC, SERVQUAL, and TBL Models towards defining the dimensions for supply chain performance assessment, and Fuzzy theory to help deal with the vague, imprecise, and subjective inputs of experts.

The BSC provides a theoretical framework to assess the performance of an organization or a supply chain through evaluation of day-to-day operations from four perspectives, i.e., financial, customer, internal business processes, and learning/growth (Bhagawat and Sharma, 2007; Kaplan and Norton, 1992).

Fig. 1: Balance Score Card -Perspectives, Adapted from Kaplan and Norton, 1992.

Likewise, the SERVQUAL model highlights the service quality dimensions, i.e., tangibility, reliability, responsiveness, assurance, and empathy, that affect the customer satisfaction levels (Obioma, 2016).

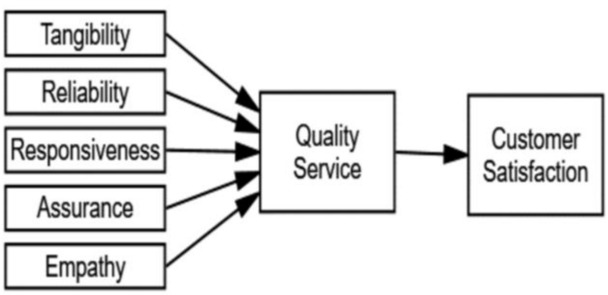

Fig. 2: The SERVQUAL Model, Adapted from Parasuraman et al. (1988).

Equally, the Triple Bottom Line model offers a thorough framework for evaluating the sustainability performance of supply chains based on environmental, social, and economic perspectives (Ahi and Searcy, 2015).

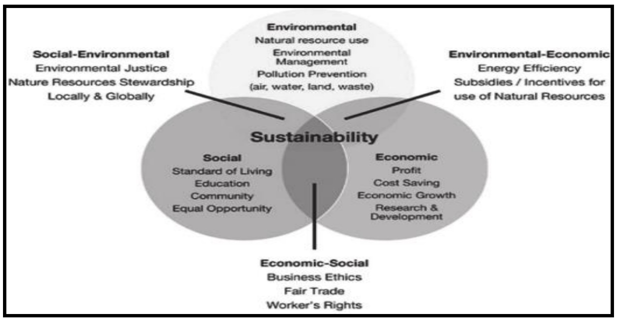

Fig. 3: Three Spheres of Sustainability, Adapted from Zak, 2015.

2.2. Related literature

Resilience stands out as a critical attribute for a cold chain, shaping its abilities (Flexibility, Agility, Adaptability, Visibility/Traceability), to not only bounce back from hindering incidents, but also enabling it to adapt accordingly (Atadoga et al., 2024; Jansen, 2024; Leończuk, 2021; Patel and Sambasivan, 2022; Rogerson and Parry, 2020; Razak et al., 2023). Equally, Sustainability fosters CCs with the ability to equally prioritize environmental responsibility, social responsibility, and economic viability (Liao et al., 2023; Kumar et al., 2022; Kumar and Choubey, 2023). Similarly, Digitalization facilitated through deployment of digital tools and technologies, aids the CCs to convene information sharing/transparency with all its stakeholders, to secure real-time data from the entire chain of activities, to trace the products history (location, condition, etc.) from its point of origin, to drive meaningful insights from the real-time data collected using mathematics, statistics, and machine learning, to remotely monitor the products and send out real-time alerts for interventions (Caro et al., 2018; Cemberci et al., 2024; Gupta et al., 2021, Ivanov et al., 2022; Lusiantoro et al., 2018; Mohammed et al., 2022; Rasool et al., 2022; Yadav et al., 2021). Besides, Product Quality facilitated through tangible infrastructural capabilities, technological capabilities, quality tools/procedures, analytical capabilities, knowledge capabilities, and certifications, assist the CCs in evaluating, tracking, and overseeing the quality of products towards safeguarding the nutrition value and face value of foods (AlMulhim, 2021; Alrae, 2024; Haleem and Shah, 2015; Joshi et al., 2024; Rajagopal, 2010; Ramos et al., 2022, Siddh et al., 2018, Sufiyan et al., 2019; Ugonna et al., 2015). In addition, Customer Service Quality guarantees client satisfaction by providing services that are tangible, dependable, responsive, confident, and empathetic in nature (Chartsutthi et al., 2024; Guo and Tsai, 2019; Kitinoja, 2013; Ramos et al., 2022; Singh et al., 2018; Sufiyan et al., 2019). Moreover, Safety enables CCs to handle food aptly, avoiding food-borne illness from contamination (Mourral and Lesaffre, 2020).

2.3. Insights from focus groups

A focus group comprising experts from the field and academia, as listed within Table 1 below, was formulated towards identifying and refining the performance criteria, ensuring their relevance and comprehensiveness (Lai et al., 2022).

Table 1: Expert Profile

Sr. No	Domain	Profile
1	Field	Vice President Operations (India's Largest Tech-Driven Cold Chain Company) with over 20 years of experience in the Supply Chain Domain.
2	Field	CEO of a Regional Cold Storage firm in India, with around 26 years of experience in the Food Industry.
3	Field	CEO of a logistics firm in India and an enterprising personality with over 31 years of experience delivering logistics solutions.
4	Field	CEO of an Ice Cream Brand in India.
5	Field	Supply Chain Professional from a baking ingredient producer in Doha, Qatar.
6	Field	Operations Professional with hands-on experience in different facets of the supply chain.
7	Field	A Digital Transformation expert from Munich, Germany.
8	Aca-demia	A Supply Chain Professional and an associate professor from a reputed university in the UK.
9	Aca-demia	A Supply Chain Professional and an associate professor from a reputed university in the UK.
10	Aca-demia	A Supply Chain Professional and an associate professor from a reputed university in the UAE.

Based on the focus group discussions, the panel of experts ultimately concluded that CCs must be exceptionally good in several key areas, such as resilience, sustainability, digitalisation, product quality, customer service quality, and safety, to achieve the intended goals of preserving the quality and availability of foods for safe human consumption.

3. Research framework

Figure 4 below presents the proposed research schema for the study.

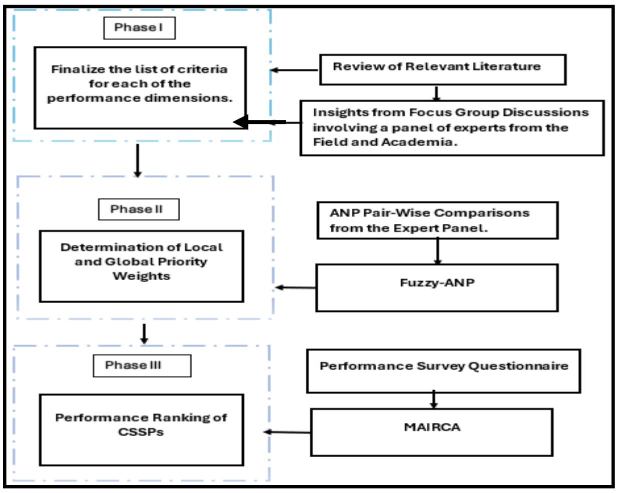

Fig. 4: Research Schema.

The study integrates FANP and MAIRCA algorithms towards assessing and ranking the performance of CSSPs, by leveraging FANP's ability to establish criteria weights within uncertain decision environments and MAIRCA's ability to rank alternatives in a robust, transparent, and scalable manner. Further, the integration is aimed at providing a comprehensive evaluation framework by capturing complexity and ambiguity while delivering reliable rankings. Wherein the Analytical Network Process (ANP) is an extension of the Analytic Hierarchy Process (AHP), it was developed to overcome the drawback of AHP towards accommodating the interdependencies among the criteria (Saaty, 1999). Additionally, the ANP can determine inner dependencies and outer dependencies, i.e., local and global relative criteria weights. Also, the ANP fosters the accommodation of both tangible and intangible criteria for comprehensive assessment and incorporation of feedback loops and interactions among criteria towards capturing dynamism within the decision environment (Sahoo and Goswami, 2023). Further, the fuzzy logic is integrated into ANP to take care of the subjectivity and uncertainty within the expert pairwise judgments (Huang, 2012).

The local and global criteria weights are determined using ANP by successfully following the steps mentioned below (Figure 5 demonstrates the flow diagram for the FANP algorithm):

Step 1 Building the Network Model →

Step 2 a. Pair-wise comparisons of the Criteria based on the Saaty's Scale of 1-9,

b. Translation of the crisp comparison values into Triangular Fuzzy Numbers,

c. Aggregation of the expert inputs using the geometric mean aggregation operator, and d. Translation of the aggregate triangular fuzzy values into crisp values →

Step 3 Evaluating the pair-wise comparison matrix of the criteria with respect to the goal and check for the matrix consistency →

Step 4 Determining each criterion's weight by considering the internal interdependencies →

Step 5 Developing a comparison matrix for the local weights →

Step 6 Finally, arriving at the sub-criteria global weights.

Fig. 5: Flow Diagram for Fuzzy ANP Algorithm.

Step 1: Development of a network structure defining interdependence among various criteria and sub-criteria (Figure 6).

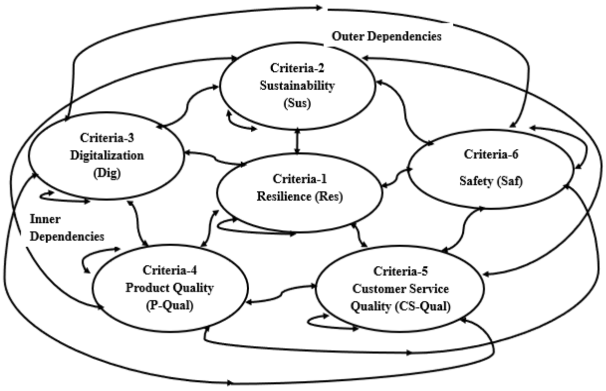

Fig. 6: ANP Cluster Network.

Step 2: The expert panel is approached to determine the relative importance of each criterion through pair-wise comparisons, assuming that there are interdependencies among them, using crisp values on Saaty's Scale of (1-9). Subsequently, fuzzy ratings of the expert inputs are determined by translation of the crisp values on Saaty's Scale into equivalent triangular fuzzy numbers using the fuzzy scale below

(Figure 7). Consequently, the expert inputs in the form of triangular fuzzy numbers are aggregated using the geometric mean aggregation operator (Figure 8).

Grade	Meaning	Triangular fuzzy expression	Inverse expression
1	Element j is equally as important as element i	(1, 1, 1)	(1, 1, 1)
2	Slightly less important	(1, 2, 3)	(1/3, 1/2, 1)
3	Slightly important	(2, 3, 4)	(1/4, 1/3, 1/2)
4	Between slightly important and more important	(3,4,5)	(1/5, 1/4, 1/3)
5	More important	(4, 5, 6)	(1/6,1/5,1/4)
6	Between more important and very important	(5, 6, 7)	(1/7, 1/6, 1,5)
7	Very important	(6, 7, 8)	(1/8, 1/7, 1/6)
8	Between very important and extremely important	(7, 8, 9)	(1/9, 1/8, 1/7)
9	Extremely important	(8, 9, 10)	(1/10, 1/9, 1/8)

Fig. 7: Rating Scale and Equivalent Fuzzy Nos., Adapted from Haber Et Al. (2018).

The Geometric Mean Aggregation Operator defined on "n" Triangular Fuzzy Number's
$\langle l_1, m_1, u_1 \rangle$, $\langle l_2, m_2, u_2 \rangle$, $\langle l_3, m_3, u_3 \rangle$, -----$\langle l_n, m_n, u_n \rangle$,
produces a Triangular Fuzzy Number $(\bar{l},\bar{m},\bar{u})$
$$\bar{l}=\left(\prod_1^n l_i\right)^{1/n},\ \bar{m}=\left(\prod_1^n m_i\right)^{1/n},\ \bar{u}=\left(\prod_1^n u_i\right)^{1/n}$$

Fig. 8: Fuzzy Aggregation, Adapted from Asady and Zendehnam, 2007.

Finally, the aggregate triangular fuzzy values are translated into crisp values using a defuzzification method, based on the nearest point of a fuzzy number (Figure 9).

The Crisp Vale $X_{A\&Z}$ equivalent to a Triangular Fuzzy Number $\widetilde{F}= (x_0, \delta, \beta)$
$$X_{A\&Z} = x_0 + (\beta - \delta)/4$$

Fig. 9: Defuzzification, Adapted from Pandey et al. (2012).

Step 3: Evaluate the pair-wise comparison matrix of the criteria with respect to the goal and check for the matrix consistency, after evaluating the weights and λ_{max} for the criteria-goal matrix.
Step 4: Determine each criterion's weight by considering the internal interdependencies (w_{inner}). Firstly, inner dependency matrices are developed. Then, based on the weights evaluated for the inner dependency matrices, a relative impact of the decision criteria matrix is generated. Consequently, the relative impact decision matrix is normalized to generate a normalized relative impact decision matrix. Following this, the normalized relative impact decision matrix is multiplied by the weights evaluated based on the criteria-goal matrix to arrive at the w_{inner} values for the criteria.
Step 5: Develop a comparison matrix for the local weights (w_{local}) of the sub-criteria with respect to their main criteria.
Step 6: Finally arrive at the sub-criteria global weights (w_{global}) using the formula below:

$$w_{global} = w_{local} \text{ x } w_{inner}$$

Step 7: Feed the criteria weights derived through ANP into the MAIRCA algorithm (Table 2), to facilitate the ranking of alternatives. Figure 10 demonstrates the flow diagram for the MAIRCA algorithm.

Step 1:
A (Raw Scores- performance scoring of alternatives against each of the criteria-initial Decision Matrix) ----> [Min-Max Normalization] ----> Tn (Normalized Matrix)
Step 2:
Defining preferences for the choice of alternatives ---->P_{Ai}
Step 3:
Weights (w) x Preferences (P) ----> Tap (Theoretical evaluation matrix)
Step 4:
Tp * Tn (Element-wise multiplication) ----> Tr (Real assessment matrix)
Step 5:
Tp - Tr ----> TD (Gap matrix)
Step 6:
Sum of TD values for each of the alternatives ----> Qi
Step 7:
Use the Qi values to compare each alternative to the best ----> *Dominance Index*
Step 8:
Evaluate the Threshold value based on the number of alternatives ----> *Dominance Threshold*
Step 9:
Compare the Dominance Index with the Dominance Threshold ----> *Final Ranking of the alternatives*

Fig. 10: Flow Diagram for the MAIRCA Algorithm.

Table 2: MAIRCA Algorithm, Adapted from Muravev et al. (2020)

Input: Initial Decision-Making Matrix indicating the values of the i^{th} alternative against j^{th} criterion/ Output: Performance Ranking of the Alternatives
Step 1: Determining the Initial Decision-Making Matrix (A), indicating the values of the i^{th} alternative against the j^{th} criterion, and evaluating a Normalized Decision Matrix (Tn) based on "A" using the min-max normalization.
Step 2: Defining preferences for the choice of alrtives P_{Ai}. Where, $P_{Ai} = \frac{1}{m}$; $\sum_{i=1}^{m} P_{Ai}$=1, i=1, 2, …, m
Step 3: The calculation of the elements of the Theoretical Evaluation Matrix (T_p). The elements of the Tp are calculated by multiplying the sub-criteria global weights w_j with the P_{Ai} for each alternative.

Table 2: MAIRCA Algorithm, Adapted from Muravev et al. (2020) Cont.

Step 4: Defining the elements of the Real Assessment Matrix (Tr) by multiplying the Theoretical Evaluation Matrix's elements (Tp) by the Normalized Decision Matrix's elements (Tn).
Step 5: Calculation of Total Difference Matrix (TD). The elements of the TD matrix are obtained as a gap between the theoretical and real ratings. Step 6: The calculation of the final values of the criteria function (Qi) by alternatives. The values of the criteria functions are obtained by summing up the gaps for each alternative. Step 7: Dominance index $A_{D,1-j}$s evaluated for each of the alternatives based on the formula below, wherein the best-ranked alernative's criterion function value is denoted by Q_1, wile the last-ranked alternative's criterion function vaue is denoted by Qn.$A_{D,1-j} = \left\|\left|Q_j\right| - \left|Q_1\right|/\left|Q_n\right|\right\|$, j = 2, 3, …, m Step 8: Once the dominance index is defined, a dominance threshold value (I_D) is evaluated based on the number of alternatives m (I_D =(m-1)/m^2). Step 9: If $A_{D,1-j}$ is greater than or equal to I_D, then the initial ranking is retained-else if $A_{D,1-j}$ is less than I_D, then the first-ranked alternative does not have enough of an advantage.

Most of the research studies opted for TOPSIS (technique for order performance by similarity to ideal solution) for ranking the alternatives. However, the method ranks alternatives based on the distances from the positive ideal solution (PIS) and negative ideal solution (NIS), and the alternative with the least distance from PIS and the greatest distance from NIS is ranked as the optimal, as per the TOPSIS. The main drawback of TOPSIS is that it evaluates distances from only two target values. Thus, it cannot claim that the best alternative is the ideal solution, as it cannot project the significance of distances from the two solutions. Hence, a relatively new method called MAIRCA was introduced by the University of Defense in Belgrade (Pamučar et al., 2014). The method was based on evaluating the gaps between the ideal and real assessments. The alternatives would be ranked based on the sum of the gaps, and the alternative with the least sum of gaps would be ranked as an optimal solution. Further, the alternative with the minimum gap would have all its criteria values closest to the ideal values. Moreover, the method produces stable and accurate results in a quicker fashion that are unaffected by rank reversal problems faced by other ranking methods and stands out as a highly scalable method providing room for additional criteria and alternatives.

4. Evaluation of the local and global criteria weights using the ANP algorithm

The local and global criteria weights were determined using the ANP steps defined within section 3.
Step 1: ANP Network Hierarchy Model (Figure 11).

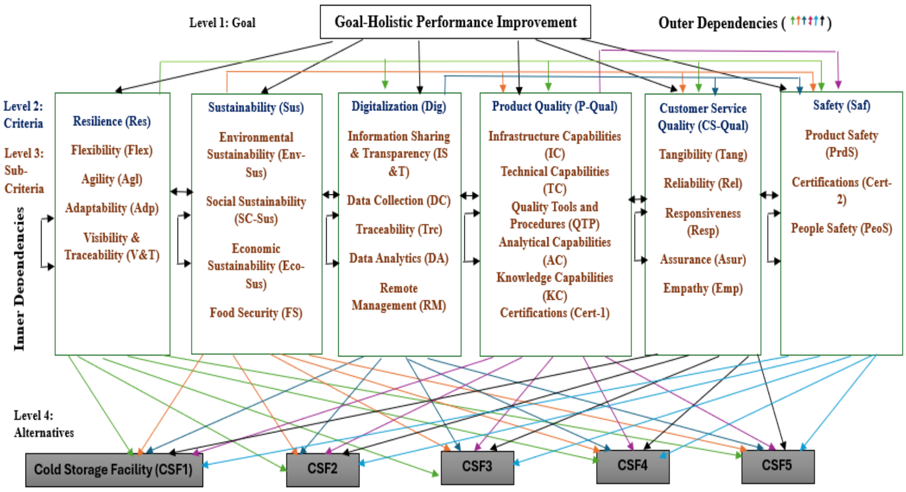

Fig. 11: ANP Network Hierarchy Model.

The ANP Network Model was formulated based on the criteria, sub-criteria, interdependencies, and interrelationships confirmed by the focus group comprising of experts from the field and academia, as listed within Table 1, towards ranking a set of hypothetical cold chain storage facilities (CSF1, CSF2, CSF3, CSF4, and CSF5).
Step 2 and 3: A pairwise comparison matrix of criteria regarding the goal (Table 3 below) was calculated based on expert pair-wise comparisons, fuzzy translation of expert crisp inputs based on Figure 7, aggregation of fuzzy translated expert inputs using geometric mean aggregation operator (Figure 8), and finally translation of the aggregate triangular fuzzy values into crisp values using a defuzzification method, based on the nearest point of a fuzzy number (Figure 9).

Table 3: Criteria-Goal Matrix

Goal-Holistic Performance Improvement	Res	Sus	Dig	P-Qual	CS-Qual	Saf
Resilience (Res)	1.00	0.39	2.75	0.15	1.44	0.16
Sustainability (Sus)	1.77	1.00	0.65	0.23	0.30	0.27
Digitalization (Dig)	0.25	1.21	1.00	0.11	0.43	0.11
Product Quality (P-Qual)	5.38	2.98	7.60	1.00	4.30	0.96
Customer Service Quality (CS-Qual)	0.50	2.75	1.46	0.17	1.00	0.17
Safety (Saf)	5.05	2.32	7.60	0.64	4.30	1.00

$\lambda_{max} = 6.1564$; CI= $(\lambda_{max} - n)/(n-1) = 0.0313$; and CR = CI/RI = 0.025.

Consequently, a standardized criteria-goal matrix (Table 4) was generated by evaluating the column-wise totals within Table 3 and then by dividing each of the matrix entities within Table 3 by its respective column-wise totals. Further, the weights were evaluated based on the row averages within Table 4.

Table 4: Standardized Criteria-Goal Matrix

Goal-Holistic Performance Improvement	Res	Sus	Dig	P-Qual	CS-Qual	Saf	Weights
Resilience (Res)	0.072	0.037	0.130	0.064	0.122	0.058	0.081
Sustainability (Sus)	0.127	0.094	0.031	0.100	0.025	0.102	0.080
Digitalization (Dig)	0.018	0.113	0.047	0.048	0.037	0.042	0.051
Product Quality (P-Qual)	0.386	0.280	0.361	0.436	0.365	0.359	0.364
Customer Service Quality (CS-Qual)	0.036	0.258	0.069	0.073	0.085	0.063	0.097
Safety (Saf)	0.362	0.218	0.361	0.278	0.365	0.375	0.327

Additionally, a consistency check (whether CR ≤ 0.1) was performed for the criteria-goal matrix through evaluation of Consistency Index (CI) and Consistency Ratio (CR) values based on the maximum eigenvalue ($\boldsymbol{\lambda_{max}}$), n-number of criteria, and RI: random index values (Figure 10 below).

n	1	2	3	4	5
RI	0	0	0.58	0.90	1.12
n	6	7	8	9	10
RI	1.24	1.32	1.41	1.45	1.49

Fig. 10: RI Values for ANP, Adapted from Chaiyaphan and Ransikarbum, 2020.

Step 4: Table 5- Table 10 representing the internal interdependency of the main criteria with respect to Resilience (Main Criteria-Res), the internal interdependency of the main criteria with respect to Sustainability (Main Criteria-Sus), the internal interdependency of the main criteria with respect to Digitalization (Main Criteria-Dig), the internal interdependency of the main criteria with respect to Product Quality (Main Criteria- P-Qual), the internal interdependency of the main criteria with respect to Customer Service Quality (Main Criteria- CS-Qual), and the internal interdependency of the main criteria with respect to Safety (Main Criteria- Saf) respectively are generated, based on fuzzy translation, aggregation, and dis-aggregation of expert crisp inputs in the form of pair-wise comparisons.

Table 5: Internal Interdependency (Main Criteria-Res) Matrix

Resilience (Res)	Sus	Dig	P-Qual	CS-Qual	Saf	Weights
Sus	1.000	0.647	0.229	0.299	0.272	0.075
Dig	1.209	1.000	0.111	0.432	0.111	0.062
P-Qual	2.977	7.605	1.000	4.299	0.956	0.394
CS-Qual	2.748	1.459	0.169	1.000	0.169	0.118
Saf	2.321	7.605	0.639	4.299	1.000	0.351

$\lambda_{max} = 5.007$; CI= $(\lambda_{max} - n)/(n-1) = 0.0016$; and CR = CI/RI = 0.001.

Table 6: Internal Interdependency (Main Criteria-Sus) Matrix

Sustainability (Sus)	Res	Dig	P-Qual	CS-Qual	Saf	Weights
Res	1.000	2.977	0.155	1.772	0.169	0.104
Dig	0.299	1.000	0.169	0.496	0.155	0.051
P-Qual	5.381	6.831	1.000	4.583	1.209	0.418
CS-Qual	0.647	1.416	0.169	1.000	0.169	0.070
Saf	5.046	6.664	0.639	4.299	1.000	0.357

$\lambda_{max} = 5.0139$; CI= $(\lambda_{max} - n)/(n-1) = 0.0035$; and CR = CI/RI = 0.003.

Table 7: Internal Interdependency (Main Criteria-Dig) Matrix

Digitalization (Dig)	Res	Sus	P-Qual	CS-Qual	Saf	Weights
Res	1.000	0.394	0.147	1.435	0.155	0.074
Sus	1.772	1.000	0.229	0.299	0.272	0.095
P-Qual	5.381	2.977	1.000	4.299	0.956	0.384
CS-Qual	0.496	2.748	0.169	1.000	0.169	0.112
Saf	5.046	2.321	0.639	4.299	1.000	0.336

$\lambda_{max} = 5.14359$; CI= $(\lambda_{max} - n)/(n-1) = 0.0359$; and CR = CI/RI = 0.032.

Table 8: Internal Interdependency (Main Criteria-P-Qual) Matrix

Product Quality (P-Qual)	Res	Sus	Dig	CS-Qual	Saf	Weights
Res	1.000	0.394	2.746	1.435	0.155	0.131
Sus	1.772	1.000	0.647	0.299	0.272	0.117
Dig	0.250	1.209	1.000	0.432	0.111	0.077
CS-Qual	0.496	2.748	1.459	1.000	0.169	0.151
Saf	5.046	2.321	7.605	4.299	1.000	0.524

$\lambda_{max} = 5.2385$; CI= $(\lambda_{max} - n)/(n-1) = 0.0596$; and CR = CI/RI = 0.053.

Table 9: Internal Interdependency (Main Criteria-CS-Qual) Matrix

Customer Service Quality (CS-Qual)	Res	Sus	Dig	P-Qual	Saf	Weights
Res	1.000	0.394	2.746	0.147	0.155	0.087
Sus	1.772	1.000	0.647	0.229	0.272	0.106
Dig	0.250	1.209	1.000	0.111	0.180	0.072
P-Qual	4.583	2.977	7.605	1.000	0.956	0.415
Saf	4.298	2.321	4.199	0.639	1.000	0.321

$\lambda_{max} = 5.031297$; CI= $(\lambda_{max} - n)/(n-1) = 0.0078$; and CR = CI/RI = 0.007.

Table 10: Internal Interdependency (Main Criteria-Saf) Matrix

Safety	Res	Sus	Dig	P-Qual	CS-Qual	Weights
Res	1.000	0.394	2.746	0.147	1.435	0.129
Sus	1.772	1.000	0.647	0.229	0.299	0.109
Dig	0.250	1.209	1.000	0.111	0.432	0.074

P-Qual	5.381	2.977	7.605	1.000	4.299	0.541
CS-Qual	0.496	2.748	1.459	0.169	1.000	0.146

$\lambda_{max} = 5.161178$; CI= $(\lambda_{max} - n)/(n-1) = 0.0403$; and CR = CI/RI = 0.036.

Consequently, the relative impact of the decision criteria matrix (Table 11) is generated based on the weights derived from Table 5- Table 10. Following this, a normalized relative impact of the decision criteria matrix (Table 12) is developed by normalizing the relative impact of the decision criteria matrix.

Table 11: Relative Impact of Decision Criteria Matrix

Relative Impact Decision Criteria	Res	Sus	Dig	P-Qual	CS-Qual	Saf
Resilience (Res)	1.000	0.104	0.074	0.131	0.087	0.129
Sustainability (Sus)	0.075	1.000	0.095	0.117	0.106	0.109
Digitalization (Dig)	0.062	0.051	1.000	0.077	0.072	0.074
Product Quality (P-Qual)	0.394	0.418	0.384	1.000	0.415	0.541
Customer Service Quality (CS-Qual)	0.118	0.070	0.112	0.151	1.000	0.146
Safety (Saf)	0.351	0.357	0.336	0.524	0.321	1.000

Table 12: Normalized Relative Impact of Decision Criteria Matrix

Normalized Relative Impact Decision Criteria	Res	Sus	Dig	P-Qual	CS-Qual	Saf
Resilience (Res)	0.5	0.052	0.037	0.066	0.043	0.064
Sustainability (Sus)	0.038	0.5	0.047	0.059	0.053	0.055
Digitalization (Dig)	0.031	0.025	0.500	0.038	0.036	0.037
Product Quality (P-Qual)	0.197	0.209	0.192	0.500	0.207	0.271
Customer Service Quality (CS-Qual)	0.059	0.035	0.056	0.076	0.500	0.073
Safety (Saf)	0.175	0.178	0.168	0.262	0.160	0.500

Finally, the criterion's weight is determined by considering the internal interdependencies (w_{inner}(Table 13) are generated by the multiplication of the Normalized relative impact of the decision criteria matrix (Table 12) with the weights obtained from the criteria-goal matrix (Table 4).

Table 13: w_{inner} Values

Resilience (Res)	0.095
Sustainability (Sus)	0.090
Digitalization (Dig)	0.060
Product Quality (P-Qual)	0.333
Customer Service Quality (CS-Qual)	0.111
Safety (Saf)	0.311

Step 5: Comparison matrices for the local weights ($\boldsymbol{w_{local}}$) The sub-criteria with respect to each of the main criteria are developed based on fuzzy translation, aggregation, and disaggregation of expert crisp inputs in the form of pair-wise comparisons. Furthermore, consistency values are evaluated for each of the matrices, respectively (Table 14-19).

Table 14: Comparison Matrix and Local Weights for Resilience

Resilience (Res)	Flex	Agl	Adp	VandT	Weights
Flexibility (Flex)	1.000	0.510	2.321	0.358	0.192
Agility (Agl)	1.416	1.000	1.625	0.570	0.252
Adaptability (Adp)	0.720	0.425	1.000	0.443	0.143
Visibility and Traceability (VandT)	2.345	1.179	3.676	1.000	0.414

$\lambda_{max} = 4.171$; CI= $(\lambda_{max} - n)/(n-1) = 0.5703$; and CR = CI/RI = 0.0634.

Table 15: Comparison Matrix and Local Weights for Sustainability

Sustainability (Sus)	EV-Sus	Scl-Sus	Eco-Sus	FS	Weights
Environmental Sustainability (EV-Sus)	1.000	0.782	2.748	0.215	0.176
Social Sustainability (Scl-Sus)	0.782	1.000	2.977	0.223	0.183
Economic Sustainability (Eco-Sus)	0.485	0.583	1.000	0.193	0.101
Food Security (FS)	3.357	3.097	4.191	1.000	0.540

$\lambda_{max} = 4.05$; CI= $(\lambda_{max} - n)/(n-1) = 0.0168$; and CR = CI/RI = 0.0187.

Table 16: Comparison Matrix and Local Weights for Digitalization

Digitalization (Dig)	ISandT	DC	Trc	DA	RM	Weights
Information Sharing/ Transparency (ISandT)	1.000	1.772	1.416	2.345	3.676	0.333
Data Collection (DC)	0.716	1.000	0.560	1.475	2.353	0.192
Traceability (Trc)	1.319	1.238	1.000	1.735	2.810	0.273
Data Analytics (DA)	0.466	0.572	0.457	1.000	1.483	0.127
Remote Management (RM)	0.295	0.278	0.326	0.437	1.000	0.074

$\lambda_{max} = 5.01813$; CI= $(\lambda_{max} - n)/(n-1) = 0.02034$; and CR = CI/RI = 0.0182.

Table 17: Comparison Matrix and Local Weights for Product Quality

Product Quality (P-Qual)	IC	TC	QTP	AC	KC	Cert-1	Weights
Tangible/Built Infrastructure Capabilities (IC)	1.000	3.676	4.191	3.357	4.298	4.191	0.444
Technical Capabilities (TC)	0.358	1.000	0.825	1.000	1.104	0.782	0.113
Quality Tools and Procedures (QTP)	0.363	0.771	1.000	0.771	1.261	0.828	0.111
Analytical Capabilities (AC)	0.358	1.000	0.825	1.000	1.104	0.738	0.112
Knowledge Capabilities (KC)	0.296	0.602	0.736	0.602	1.000	0.651	0.087
Certifications (Cert-1)	0.511	0.782	0.891	1.207	1.483	1.000	0.133

$\lambda_{max} = 6.0763$; CI= $(\lambda_{max} - n)/(n-1) = 0.0153$; and CR = CI/RI = 0.012.

Table 18: Comparison Matrix and Local Weights for Customer Service Quality

Customer Service Quality (CS-Qual)	Tang	Rel	Resp	Asur	Emp	Weights
Tangibility (Tang)	1.000	0.440	0.639	0.247	0.268	0.083
Reliability (Rel)	1.587	1.000	1.104	0.531	0.454	0.152
Responsiveness (Resp)	0.956	0.602	1.000	0.477	0.381	0.116
Assurance (Asur)	2.803	1.626	2.151	1.000	0.687	0.265
Empathy (Emp)	2.436	4.299	2.131	1.772	1.000	0.384

$\lambda_{max} = 5.097$; CI= $(\lambda_{max} - n)/(n-1) = 0.0243$; and CR = CI/RI = 0.022.

Table 19: Comparison Matrix and Local Weights for Safety

Safety (Saf)	PrdS	Cert-1	PeoS	Weights
Product Safety (PrdS)	1.000	2.436	0.357	0.282
Certifications (Cert-2)	0.440	1.000	0.357	0.159
People Safety (PeoS)	2.345	3.097	1.000	0.559

$\lambda_{max} = 3.085$; CI= $(\lambda_{max} - n)/(n-1) = 0.0425$; and CR = CI/RI = 0.07.

Step 6: Finally, sub-criteria global weights using the formula below: w_{global} $(Table\ 20)$ = w_{local} x w_{inner}

Table 20: Sub-Criteria Global Weights

Criteria	w_{inner}	Sub-Criteria	w_{local}	w_{global}
Resilience (Res)	0.095	Flexibility (Flex)	0.192	0.018
		Agility (Agl)	0.252	0.024
		Adaptability (Adp)	0.143	0.014
		Visibility and Traceability (VandT)	0.414	0.040
Sustainability (Sus)	0.090	Environmental Sustainability (EV-Sus)	0.176	0.016
		Social Sustainability (Scl-Sus)	0.183	0.016
		Economic Sustainability (Eco-Sus)	0.101	0.009
		Food Security (FS)	0.540	0.048
Digitalization (Dig)	0.060	Information Sharing/ Transparency (ISandT)	0.333	0.020
		Data Collection (DC)	0.192	0.011
		Traceability (Trc)	0.273	0.016
		Data Analytics (DA)	0.127	0.008
		Remote Management (RM)	0.074	0.004
Product Quality (P-Qual)	0.333	Tangible/Built Infrastructure Capabilities (IC)	0.444	0.148
		Technical Capabilities (TC)	0.113	0.038
		Quality Tools and Procedures (QTP)	0.111	0.037
		Analytical Capabilities (AC)	0.112	0.037
		Knowledge Capabilities (KC)	0.087	0.029
		Certifications (Cert-1)	0.133	0.044
Customer Service Quality (CS-Qual)	0.111	Tangibility (Tang)	0.083	0.009
		Reliability (Rel)	0.152	0.017
		Responsiveness (Resp)	0.116	0.013
		Assurance (Asur)	0.265	0.029
		Empathy (Emp)	0.384	0.042
Safety (Saf)	0.311	Product Safety (PrdS)	0.282	0.088
		Certifications (Cert-2)	0.159	0.050
		People Safety (PeoS)	0.559	0.174

5. Cold storage performance survey questionnaire

The survey questionnaire used to holistically assess a cold storage facility across multiple dimensions is appended as Appendix I.

6. Performance benchmarking

The proposed framework integrating ANP and MAIRCA was used for benchmarking the performance of a set of hypothetical CSSPs, based on the scores synthetically generated about alignment with the attributes listed under each of the sub-criterion within the performance survey questionnaire (Section 5 and Appendix I).

Step 1: A Decision Matrix "A" (Table 21) is formulated below, based on the scores evaluated for each alternative against each of the sub-criterion. A = $[\boldsymbol{a_{ij}}]_{m*n}$= $\begin{bmatrix} \boldsymbol{a_{11}} & \cdots & \boldsymbol{a_{1n}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{a_{m1}} & \cdots & \boldsymbol{a_{mn}} \end{bmatrix}$ i = 1, 2, …m; j= 1,2, …n; Wherein, $\boldsymbol{a_{ij}}$ represents the performance of the ith alternative according to the jth criterion.

Table 21: Initial Decision Matrix (A)-Synthetically Generated Based on the Survey Questionnaire

	Res				Sus				Dig					P-Qual						CS-Qual					Saf		
	Flex	Agl	Adp	V&T	EV	Scl	Eco	FS	IS&T	DC	Trc	DA	RM	IC	TC	QTP	AC	KC	Cert1	Tang	Rel	Resp	Asur	Emp	PrdS	Cert2	PeoS
CSF1	0.58	0.6	0.75	0.71	0.7	0.83	0.83	0.8	0.66	0.66	0.75	0.75	0.5	0.57	0.83	0.85	0.5	0.71	0.5	0.66	0.75	0.6	0.81	0.8	0.71	0.75	0.69
CSF2	0.66	0.8	0.62	0.85	0.6	0.66	0.66	0.6	0.5	0.5	0.5	0.5	1	0.71	0.66	0.71	0.75	0.85	0.5	0.83	0.87	0.8	0.9	0.6	0.64	1	0.84

CSF3	0.83	0.8	0.75	0.57	0.8	0.5	0.66	0.7	0.83	0.83	0.75	0.75	1	0.85	0.5	0.57	0.75	0.57	1	1	0.62	0.6	0.72	1	0.71	0.5	0.61
CSF4	0.66	0.8	0.87	0.57	0.7	0.83	0.5	0.8	0.5	0.5	0.5	0.5	0.5	0.85	0.83	0.85	0.25	0.71	1	0.83	0.87	0.4	0.63	0.6	0.78	0.75	0.76
CSF5	0.75	0.6	0.62	0.71	0.6	0.66	0.83	0.6	0.66	0.66	0.75	0.75	1	0.57	0.66	0.71	0.5	0.85	0.5	0.66	0.75	0.6	0.72	0.8	0.57	0.5	0.61
Min	0.58	0.6	0.62	0.57	0.6	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.57	0.5	0.57	0.25	0.57	0.5	0.66	0.62	0.4	0.63	0.6	0.57	0.5	0.61
Max	0.83	0.8	0.87	0.85	0.8	0.83	0.83	0.8	0.83	0.83	0.75	0.75	1	0.85	0.83	0.85	0.75	0.85	1	1	0.87	0.8	0.9	1	0.78	1	0.84
Max-Min	0.25	0.2	0.25	0.28	0.2	0.33	0.33	0.2	0.33	0.33	0.25	0.25	0.5	0.28	0.33	0.28	0.5	0.28	0.5	0.34	0.25	0.4	0.27	0.4	0.21	0.5	0.23

Step 2: Considering all the criteria belong to a benefit category, a Normalized Decision Matrix "Tn" (Table 22) is formulated using the formula below: $\frac{a_{ij}-a_i^{min}}{a_i^{max}-a_i^{min}}$ Wherein, $\boldsymbol{a_{ij}}$, $\boldsymbol{a_i^{max}}$, and $\boldsymbol{a_i^{min}}$ represent the elements of the initial decision matrix (Table 21).

Table 22: Normalized Decision Matrix (Tn)

	Res				Sus				Dig					P-Qual						CS-Qual					Saf		
	Flex	Agl	Adp	V&T	EV	Scl	Eco	FS	IS&T	DC	Trc	DA	RM	IC	TC	QTP	AC	KC	Cert1	Tang	Rel	Resp	Asur	Emp	PrdS	Cert2	PeoS
CSF1	0.00	0.00	0.52	0.50	0.50	1.00	1.00	1.00	0.48	0.48	1.00	1.00	0.00	0.00	1.00	1.00	0.50	0.51	0.00	0.00	0.52	0.50	0.67	0.50	0.67	0.50	0.35
CSF2	0.32	1.00	0.00	1.00	0.00	0.48	0.48	0.00	0.00	0.00	0.00	0.00	1.00	0.50	0.48	0.50	1.00	1.00	0.00	0.50	1.00	1.00	1.00	0.00	0.33	1.00	1.00
CSF3	1.00	1.00	0.52	0.00	1.00	0.00	0.48	0.50	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	1.00	0.00	1.00	1.00	0.00	0.50	0.33	1.00	0.67	0.00	0.00
CSF4	0.32	1.00	1.00	0.00	0.50	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.50	1.00	0.50	1.00	0.00	0.00	0.00	1.00	0.50	0.65
CSF5	0.68	0.00	0.00	0.50	0.00	0.48	1.00	0.00	0.48	0.48	1.00	1.00	1.00	0.00	0.48	0.50	0.50	1.00	0.00	0.00	0.52	0.50	0.33	0.50	0.00	0.00	0.00

Step 3: Evaluate P_{Ai} using the formula below

$P_{Ai} = \frac{1}{m}$; $\sum_{i=1}^{m} P_{Ai}$=1, i=1, 2, …, m, wherein m represents the number of alternatives (P_{Ai}= 1/5).

Step 4: Multiply the sub-criteria global weights evaluated within step 6 of section 4 (Table 20) with the $\boldsymbol{P_{Ai}}$ for each alternative to arrive at the Theoretical Evaluation Matrix "Tp" (Table 23).

Table 23: Theoretical Evaluation Matrix (Tp)

	Res				Sus				Dig					P-Qual						CS-Qual					Saf		
	Flex	Agl	Adp	V&T	EV	Scl	Eco	FS	IS&T	DC	Trc	DA	RM	IC	TC	QTP	AC	KC	Cert1	Tang	Rel	Resp	Asur	Emp	PrdS	Cert2	PeoS
CSF1	0.004	0.005	0.003	0.008	0.003	0.003	0.002	0.010	0.004	0.002	0.003	0.002	0.001	0.030	0.008	0.007	0.007	0.006	0.009	0.002	0.003	0.003	0.006	0.008	0.018	0.010	0.035
CSF2	0.004	0.005	0.003	0.008	0.003	0.003	0.002	0.010	0.004	0.002	0.003	0.002	0.001	0.030	0.008	0.007	0.007	0.006	0.009	0.002	0.003	0.003	0.006	0.008	0.018	0.010	0.035
CSF3	0.004	0.005	0.003	0.008	0.003	0.003	0.002	0.010	0.004	0.002	0.003	0.002	0.001	0.030	0.008	0.007	0.007	0.006	0.009	0.002	0.003	0.003	0.006	0.008	0.018	0.010	0.035
CSF4	0.004	0.005	0.003	0.008	0.003	0.003	0.002	0.010	0.004	0.002	0.003	0.002	0.001	0.030	0.008	0.007	0.007	0.006	0.009	0.002	0.003	0.003	0.006	0.008	0.018	0.010	0.035

CSF5	0.004	0.005	0.003	0.008	0.003	0.003	0.002	0.010	0.004	0.002	0.003	0.002	0.001	0.030	0.008	0.007	0.007	0.006	0.009	0.002	0.003	0.003	0.006	0.008	0.018	0.010	0.035

Step 5: The Real Assessment Matrix "Tr" (Table 24) is evaluated by multiplying the Theoretical Evaluation Matrix's (Tp) elements (Table 23) by the Normalized Decision Matrix's (Tn) elements (Table 22).

Table 24: The Real Assessment Matrix (Tr)

	Res				Sus			Dig					P-Qual						CS-Qual						Saf		
	Flex	Agl	Adp	V&T	EV	Scl	Eco	FS	IS&T	DC	Trc	DA	RM	IC	TC	QTP	AC	KC	Cert1	Tang	Rel	Resp	Asur	Emp	PrdS	Cert2	PeoS
CSF1	0.000	0.000	0.001	0.004	0.002	0.003	0.002	0.010	0.002	0.001	0.003	0.002	0.000	0.000	0.008	0.007	0.004	0.003	0.000	0.000	0.002	0.001	0.004	0.004	0.012	0.005	0.012
CSF2	0.001	0.005	0.000	0.008	0.000	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.015	0.004	0.004	0.007	0.006	0.000	0.001	0.003	0.003	0.006	0.000	0.006	0.010	0.035
CSF3	0.004	0.005	0.001	0.000	0.003	0.000	0.001	0.005	0.004	0.002	0.003	0.002	0.001	0.030	0.000	0.000	0.007	0.000	0.009	0.002	0.000	0.001	0.002	0.008	0.012	0.000	0.000
CSF4	0.001	0.005	0.003	0.000	0.002	0.003	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.030	0.008	0.007	0.000	0.003	0.009	0.001	0.003	0.000	0.000	0.000	0.018	0.005	0.023
CSF5	0.002	0.000	0.000	0.004	0.000	0.002	0.002	0.000	0.002	0.001	0.003	0.002	0.001	0.000	0.004	0.004	0.004	0.006	0.000	0.000	0.002	0.001	0.002	0.004	0.000	0.000	0.000

Step 6: The Total Difference Matrix "TD" (Table 25) is evaluated by subtracting the elements of the Tr from the elements of the Tp. The TD matrix below lists the g_{ij} elements, wherein $Tp_{ij} – Tr_{ij}$.

Table 25: Total Difference Matrix (TD)

	Res				Sus			Dig					P-Qual						CS-Qual						Saf		
	Flex	Agl	Adp	V&T	EV	Scl	Eco	FS	IS&T	DC	Trc	DA	RM	IC	TC	QTP	AC	KC	Cert1	Tang	Rel	Resp	Asur	Emp	PrdS	Cert2	PeoS
CSF1	0.004	0.005	0.001	0.004	0.002	0.000	0.000	0.000	0.002	0.001	0.000	0.000	0.001	0.030	0.000	0.000	0.004	0.003	0.009	0.002	0.002	0.001	0.002	0.004	0.006	0.005	0.023
CSF2	0.002	0.000	0.003	0.000	0.003	0.002	0.001	0.010	0.004	0.002	0.003	0.002	0.000	0.015	0.004	0.004	0.000	0.000	0.009	0.001	0.000	0.000	0.000	0.008	0.012	0.000	0.000
CSF3	0.000	0.000	0.001	0.008	0.000	0.003	0.001	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.007	0.000	0.006	0.000	0.000	0.003	0.001	0.004	0.000	0.006	0.010	0.035
CSF4	0.002	0.000	0.000	0.008	0.002	0.000	0.002	0.000	0.004	0.002	0.003	0.002	0.001	0.000	0.000	0.000	0.007	0.003	0.000	0.001	0.000	0.003	0.006	0.008	0.000	0.005	0.012
CSF5	0.001	0.005	0.003	0.004	0.003	0.002	0.000	0.010	0.002	0.001	0.000	0.000	0.000	0.030	0.004	0.004	0.004	0.000	0.009	0.002	0.002	0.001	0.004	0.004	0.018	0.010	0.035

Step 7: The criteria function for the alternatives Qi is evaluated based on the values from TD matrix using the formula below. Then the initial ranking of the alternatives is determined based on the Qi values computed, wherein the alternative with the lowest Qi value is ranked as the best alternative. Consequently, the dominance index $A_{D,1\text{-}j}$ is evaluated for each of the alternatives based on the formula below, wherein the best-ranked alternative's criterion function value is denoted by Q_1, while the last-ranked alternative's criterion function value is denoted by Qn. Furthermore, a dominance threshold value (I_D) is evaluated based on the number of alternatives m (I_D =(m-1)/m^2).

$Q_i = \sum_{j=1}^{n} g_{ij}$, i = 1, 2, …, m

$A_{D,1-j} = \left||Q_j| - |Q_1|/|Q_n|\right|$, j = 2, 3, …, m

Finally, the revised ranking of alternatives is determined based on comparison of the dominance index values and the I_D value. The initial ranking of the alternative remains unchanged if the dominance index value for that alternative is greater than the I_D value, in contrast if the dominance index value for that alternative is smaller than the I_D value, then the initial ranking stands invalid and need to be updated since it is impossible to claim with certainty that the first-ranked alternative is superior than the alternative under comparison. For example, based on Table 26 below the dominance index value for the secondly ranked alternative is smaller than the I_D value, hence it is re-ranked as 1*.

Table 26: Final Ranking of Alternatives (MAIRCA)

	CSF1	CSF2	CSF3	CSF4	CSF5
Qi	0.109	0.084	0.098	0.071	0.155
Initial Ranking	4	2	3	1	5
AD,1−j (Dominance Index)	0.244	0.084	0.18	0	0.543
I_D (Dominance Index)	0.16				
Revised Ranking	4	1*	3	1	5
Final Ranking	CSF4≈CSF2>CSF3>CSF1>CSF5				

7. Conclusion and future research avenues

The study aided with the determination of a thorough set of criteria for evaluating CSSPs performance in relation to dimensions derived from the integration of literature, SERVQUAL, TBL, and the BSC models. Additionally, the study aided with the finalization of a set of performance evaluation criteria through focus groups with academic and industry professionals in accordance with decision makers' needs for creating a trustworthy, useful, and realistic methodological framework. Besides, the study facilitated with the development of a comprehensive assessment methodology and a novel performance analysis procedure that could be used as a mathematical instrument to evaluate a CSSPs overall performance through the integration of FANP and MAIRCA MCDM approaches. In addition, the study also provides a holistic assessment framework in the form of a survey questionnaire, which could be used along with the criteria weights generated through the Fuzzy ANP to rank and benchmark the performance of CSSPs using the MAIRCA method. Further, the study conceptualized a hybrid model, that could be embraced by the supply chain stakeholders to identify performance gaps within real-world scenarios and consequently enlist all the strategies needful to address the performance gaps based on the best practices (i.e., performance differentiators). However, the study uses synthetic data towards scoring of performance attributes for five hypothetical cold storage service providers in order to demonstrate the application of the novel integrated model for ranking and benchmarking. Hence, their lies a need to present case illustrations within real-world cold storage service providers across multiple geographies to exhibit the model applicability towards determination of performance gaps within real-life scenarios and towards formulation of rightful strategies to address the gaps identified. Additionally, longitudinal studies are also recommended to test the efficacy of the strategies suggested for performance enhancements. Likewise, there lies a requirement to perform a comparative assessment of the alternative ranking using other MCDM approaches such as VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) and EDAS (evaluation based on distance from average solution). Furthermore, there lies a future scope for sensitivity analysis to validate consistency and ranking stability.

8. Data availability statement

The article's content includes all of the data estimated and analysed within the course of the study. Additional to what is presented within the manuscript, no other datasets have been generated or used.

References

[1] Abaasa, P. (2023). Assessment of the cold chain capacity used in bulk handling of perishable agricultural produce in Uganda (*Doctoral dissertation, Kyambogo University* [unpublished work]).

[2] Abdulla, A., & Baryannis, G. (2024). A hybrid multi-criteria decision-making and machine learning approach for explainable supplier selection. *Supply Chain Analytics*, *7*, 100074. https://doi.org/10.1016/j.sca.2024.100074.

[3] Abu-Nahel, Z. O., Alagha, W. H., Al Shobaki, M. J., Abu-Naser, S. S., and El Talla, S. A. (2020). Flexibility of Information and Its Relationship to Improving the Quality of Service. *International Journal of Engineering and Information Systems*, 4(8), 214-234.

[4] Adler. S. R., Zinn. T. (2021). Vacuum Plumbing for Safe, Sustainable and Future-Ready Plumbing Design. *ASPE Tech Symposium 2021*.

[5] Agnihotri, R., Kalra, A., Agnihotri Chen, H., and Daugherty, P. J. (2022). Utilizing social media in a supply chain B2B setting: A knowledge perspective. *Journal of Business logistics*, 43(2), 189-208. https://doi.org/10.1111/jbl.12289.

[6] Ahi, P., and Searcy, C. (2015). Assessing sustainability in the supply chain: A triple bottom line approach. *Applied Mathematical Modelling*. 39. https://doi.org/10.1016/j.apm.2014.10.055.

[7] Ahmad, S. A. H., Ab Rahman, M. N., & Muhamed, A. A. (2020, August). Optimal temperature in cold storage for perishable foods. In *Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management* (pp. 3449-3456). Southfield, MI, USA: IEOM Society International.

[8] Alastal, H., Sharaf, A., Mahmoud, S., Alsaidi, O., & Bahroun, Z. (2025). Integrating Multiple Criteria Decision-Making Techniques in Sustainable Supplier Selection: A Comprehensive Review. *Decision Making: Applications in Management and Engineering*, 380-400.

[9] Ali, S. I., Lalji, S. M., Hashmi, S., Awan, Z., Iqbal, A., and Al-Ammar, E. A. (2024). Risk quantification and ranking of oil fields and wells facing asphaltene deposition problem using fuzzy TOPSIS coupled with AHP. *Ain Shams Engineering Journal*, *15*(1), 102289. https://doi.org/10.1016/j.asej.2023.102289.

[10] AlMulhim, A. F. (2021). Smart supply chain and firm performance: the role of digital technologies. *Business Process Management Journal*, 27(5), 1353-1372. https://doi.org/10.1108/BPMJ-12-2020-0573.

[11] Alrae, R. (2024). Quality Tools, Technologies, and Techniques: Enhancing Product and Service Excellence. https://doi.org/10.5772/intechopen.113994

[12] Alrashoud, M., AlMeshary, M., and Abhari, A. (2015, April). Automatic validation for multi criteria decision making models in simulation environments. In *Proceedings of the 18th Symposium on Communications and Networking* (pp. 44-47b).

[13] Anttonen, H., Pekkarinen, A., and Niskanen, J. (2009). Safety at work in cold environments and prevention of cold stress. *Industrial health*, 47(3), 254-261. https://doi.org/10.2486/indhealth.47.254

[14] Ap Tech Group. (2025). Solid Chemistry Water Treatment. *Ap Tech Solids*. Available at: https://www.aptechgroup.com/wp-content/uploads/Cold-Storage-Solid-Chemistry.pdf (Accessed, Jan 20, 2025).

[15] Asady, B., & Zendehnam, A. (2007). Ranking fuzzy numbers by distance minimization. *Applied Mathematical Modelling*, *31*(11), 2589-2598. https://doi.org/10.1016/j.apm.2006.10.018

[16] Atadoga, A., Osasona, F., Amoo, O. O., Farayola, O. A., Ayinla, B. S., and Abrahams, T. O. (2024). The role of IT in enhancing supply chain resilience: a global review. *International Journal of Management and Entrepreneurship Research*, 6(2), 336-351. https://doi.org/10.51594/ijmer.v6i2.774

[17] Atkins, R., Deranek, K., and Nonet, G. (2018). Supply chain food waste reduction and the triple bottom line. *Social business*, 8(2), 121-144. https://doi.org/10.1362/204440818X15208755029645

[18] Aung, M. M., and Chang, Y. S. (2014). Temperature management for the quality assurance of a perishable food supply chain. *Food Control*, 40, 198-207. https://doi.org/10.1016/j.foodcont.2013.11.016

[19] Aung, M. M., and Chang, Y. S. (2022). Cold chain monitoring tools. *In Cold Chain Management* (pp. 77-91). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-09567-2_5

[20] Aziz, M. A., Khan, M. I. H., Afroz, H. M., Hossain, M. M., Talukdar, S., and Masud, M. A. A. (2024). The development and performance evaluation of an alternative energy-based hybrid cold storage system. *Journal of Cleaner Production*, 434, 140394. https://doi.org/10.1016/j.jclepro.2023.140394

[21] Bearg, D. W. (2019). *Indoor air quality and HVAC systems*. Routledge. https://doi.org/10.1201/9780203751152

[22] Bhagawat, R., and Sharma, M.K. (2007). Performance measurement of supply chain management: A balanced scorecard approach. *Computers and Industrial Engineering*, 53(1), 43-62. https://doi.org/10.1016/j.cie.2007.04.001

[23] Bishnoi, R., and Aharwal, K. R. (2024). Experimental investigation of effect of ventilation strategies on the performance of cold storage. *Heat Transfer*, 53(2), 346-362. https://doi.org/10.1002/htj.22954

[24] Boonsupthip, W., Heldman, D. R., and Choachamnan, J. (2015). Quality monitoring and management during storage and distribution of frozen vegetables. *Handbook of vegetable preservation and processing*, 349-376.

[25] Brzozowska, A., Brzeszczak, A., Imiołczyk, J., and Szymczyk, K. (2016, June). Managing cold supply chain. *In 5th IEEE International Conference on Advanced Logistics and Transport (ICALT 2016)*.

[26] Caro, M. P., Ali, M. S., Vecchio, M., and Giaffreda, R. (2018, May). Blockchain-based traceability in Agri-Food supply chain management: A practical implementation. *In 2018 IoT Vertical and Topical Summit on Agriculture-Tuscany (IOT Tuscany)* (pp. 1-4). IEEE. https://doi.org/10.1109/IOT-TUSCANY.2018.8373021

[27] Cemberci, M., Cicek Vural, S., Celik, C., and Canbaz, E. (2024). The Role of Supply Chain Transparency in the Relation between Supply Chain Analytics Capabilities and Firm Performance. *Operations and Supply Chain Management: An International Journal*, 17(2), 253-263. https://doi.org/10.31387/oscm0570426

[28] Chaiyaphan, C., and Ransikarbum, K. (2020). Criteria analysis of food safety using the Analytic Hierarchy Process (AHP)-a case study of Thailand's fresh markets. In *E3S Web of Conferences* (Vol. 141, p. 02001). EDP Sciences. https://doi.org/10.1051/e3sconf/202014102001

[29] Charles, D. (2020). Cold storage work and cold protective gloves–a review.

[30] Chartsutthi, P., Ngoendee, T., Kham, N. K., Kamhangwong, D., Khuanmuang, S., and Yamsa-ard, S. (2024, December). What Drives Customer Satisfaction in Cold Chain Logistics? A Cross-Industry Analysis of Food and Pharmaceutical Sectors. In *2024 International Conference on Decision Aid Sciences and Applications (DASA)* (pp. 1-4). IEEE. https://doi.org/10.1109/DASA63652.2024.10836322

[31] Chihana, S., Phiri, J., and Kunda, D. (2018). An IoT based warehouse intrusion detection (E-Perimeter) and grain tracking model for food reserve agency. *International Journal of Advanced Computer Science and Applications*, 9(9). https://doi.org/10.14569/IJACSA.2018.090929

[32] de Sá Silva, A. C. R., Bimbato, A. M., Balestieri, J. A. P., and Vilanova, M. R. N. (2022). Exploring environmental, economic and social aspects of rainwater harvesting systems: A review. *Sustainable Cities and Society*, 76, 103475. https://doi.org/10.1016/j.scs.2021.103475

[33] Dzyvak, T. R., and Vovk, Y. Y. (2023). Modular systems of conveyors for transport and warehouse operations.

[34] Fauadi, M. H. F. M., Anuar, N. I., Kurniawati, D. A., Rosyidi, C. N., Abdullah, L., Damanhuri, A. A. M., & Tay, S. J. (2025). Recent advances in multi-criteria decision-making approaches for circular supply chains: A comprehensive review. *Multidisciplinary Reviews*, *9*(2), 2026087.

[35] Fikiin, K., and Markov, D. (2014). Efficient loading and unloading of a food cold store. *New Food Magazine*, 6.

[36] Friedman-Heiman, A., and Miller, S. A. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. *Environmental Research Letters*, 19(6), 064038. https://doi.org/10.1088/1748-9326/ad4c7b

[37] Füchtenhans, M., Grosse, E. H., and Glock, C. H. (2021). Smart lighting systems: state-of-the-art and potential applications in warehouse order picking. *International Journal of Production Research*, 59(12), 3817-3839. https://doi.org/10.1080/00207543.2021.1897177

[38] Garg, M., Sharma, S., Chopra, R., and Sadhu, S. D. (2021). Sanitation and Hygiene Process in Storage. *In Packaging and Storage of Fruits and Vegetables* (pp. 209-233). Apple Academic Press. https://doi.org/10.1201/9781003161165-10

[39] Guo, S. M., and Tsai, K. M. (2019). Cold chain operational standards and a certification case study in Taiwan. *In Symposium on Logistics* (Vol. 447).

[40] Gupta, H., Kumar, S., Kusi-Sarpong, S., Jabbour, C. J. C., and Agyemang, M. (2021). Enablers to supply chain performance on the basis of digitization technologies. *Industrial Management & Data Systems,* 121(9), 1915-1938. https://doi.org/10.1108/IMDS-07-2020-0421

[41] Gurrala, K., and Gonela, S. (2025). A Systematic Literature Review of Muti-Criteria Decision-Making Applications within Food Supply Chains using the TCM-ADO Framework. International Journal of Mathematical, Engineering and Management Sciences, 10(6), XXX-XXX (In Print).

[42] Gwynne, R. (2014). *Warehouse management: a complete guide to improving efficiency and minimizing costs in the modern warehouse*. Kogan Page Limited.

[43] Haber, N., Fargnoli, M., Tronci, M., and Ababneh, A. (2018). Managing customer requirements for an effective service implementation in a Product-Service System (PSS). In *Proceedings of the 2nd IEOM European Conference on Industrial Engineering and Operations Management, Paris, France* (pp. 26-27).

[44] HALEEM, F., and SHAH, S. T. H. (2015). Worker, Work, and Work Dynamics: The Role of Multi-skilled, Proactive, and Customer-Focused Staff. *Journal of Business and Tourism*, 1(2), 79-88.

[45] Hertog, M. L., Uysal, I., McCarthy, U., Verlinden, B. M., and Nicolaï, B. M. (2014). Shelf-life modelling for first-expired-first-out warehouse management. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2017), 20130306. https://doi.org/10.1098/rsta.2013.0306

[46] Hienen, L. R. C. (2024). *Building an Effective Warehouse Dashboard: Improving Operational Insight Through KPIs* (Bachelor's thesis, University of Twente).

[47] Hoang, D. K., and Carson, J. K. (2024). *Air blast freezing in the food industry. In Low-Temperature Processing of Food Products* (pp. 117-146). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-818733-3.00004-7

[48] Hofstra, N., Petkova, B., Dullaert, W., Reniers, G., and De Leeuw, S. (2018). Assessing and facilitating warehouse safety. *Safety Science*, 105, 134-148. https://doi.org/10.1016/j.ssci.2018.02.010

[49] Huang, J.J. (2012). A mathematical programming model for the fuzzy analytic network process—applications of international investment. *The Journal of the Operational Research Society*, 63 (11), 1534-1544. https://doi.org/10.1057/jors.2011.164

[50] Ivanov, D., Dolgui, A., and Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service". *Transportation Research Part E: Logistics and Transportation Review*, 160, 102676. https://doi.org/10.1016/j.tre.2022.102676

[51] Jack, E. P., and Raturi, A. (2002). Sources of volume flexibility and their impact on performance. *Journal of operations management*, 20(5), 519-548. https://doi.org/10.1016/S0272-6963(01)00079-1

[52] Jansen, W. M. (2024). *Assessing supply chain resilience capabilities among manufacturing firms: a closer look on supply chain flexibility* (Master's thesis, University of Twente).

[53] Jermsittiparsert, K., Sutduean, J., and Sriyakul, T. (2019). Role of warehouse attributes in supply chain warehouse efficiency in Indonesia. *International journal of innovation, creativity and change*, 5(2), 786-802.

[54] Joshi, M., Naaz, S., and Joshi, P. (2024). Food Safety and Security in India: Prospectous and Challenges.
[55] Kabir, M. A., Khan, S. A., Gunasekaran, A., & Mubarik, M. S. (2025). Multi-criteria decision making to explore the relationship between supply chain mapping and performance. *Decision Analytics Journal*, 100577. https://doi.org/10.1016/j.dajour.2025.100577
[56] Kafetzopoulos, D., Vouzas, F., and Skalkos, D. (2020). Developing and validating an innovation drivers' measurement instrument in the agri-food sector. *British Food Journal*, 122(4), 1199-1214. https://doi.org/10.1108/BFJ-09-2019-0721
[57] Kale, S. D., and Patil, S. C. (2021). Need for predictive data analytics in cold chain management. In *Advances in VLSI and Embedded Systems*: *Select Proceedings of AVES* 2019 (pp. 115-129). Springer Singapore. https://doi.org/10.1007/978-981-15-6229-7_9
[58] Kaplan, R., and Norton, D. (1992) The Balanced Scorecard—Measures That Drive Performance. *Harvard Business Review*, 79.
[59] Kazançoğlu, Yiğit and Sagnak, Muhittin and Mangla, Sachin and Sezer, Deniz and Özbiltekin, Melisa. (2021). A fuzzy based hybrid decision framework to circularity in dairy supply chains through big data solutions. Technological Forecasting and Social Change. 170. 120927.. https://doi.org/10.1016/j.techfore.2021.120927
[60] Khan, S. A. R., Yu, Z., Rehman Khan, S. A., and Yu, Z. (2019). Warehousing and Storage Equipment. *Strategic Supply Chain Management*, 81-107.
[61] Kitinoja, L. (2013). Use of cold chains for reducing food losses in developing countries. *Population*, 6(1.23), 5-60. https://doi.org/10.1007/978-3-030-15058-7_4
[62] Kumar, M., and Choubey, V. K. (2023). Sustainable performance assessment towards sustainable consumption and production: evidence from the Indian dairy industry. *Sustainability*, 15(15), 11555. https://doi.org/10.3390/su151511555
[63] Kumar, R., & Pamucar, D. (2025). A comprehensive and systematic review of multi-criteria decision-making (MCDM) methods to solve decision-making problems: two decades from 2004 to 2024. *Spectrum of Decision Making and Applications*, *2*(1), 178-197. https://doi.org/10.31181/sdmap21202524
[64] Kumar, M., Sharma, M., Raut, R. D., Mangla, S. K., and Choubey, V. K. (2022). Performance assessment of circular driven sustainable agri-food supply chain towards achieving sustainable consumption and production. *Journal of Cleaner Production*, 372, 133698. https://doi.org/10.1016/j.jclepro.2022.133698
[65] Kumar, N., Tyagi, M., and Sachdeva, A. (2023). A sustainable framework development and assessment for enhancing the environmental performance of cold supply chain. *Management of Environmental Quality: An International Journal*, 34(4), 1077-1110. https://doi.org/10.1108/MEQ-03-2022-0046
[66] Kurien, G. P., and Qureshi, M. N. (2015). Analysis and measurement of supply chain flexibility. *International Journal of Logistics Systems and Management*, 21(1), 70-91. https://doi.org/10.1504/IJLSM.2015.069078
[67] Kurniawan, M. R., Hadiyanto, H., Zulkarnaen, J. D. P., and Harito, C. (2024). Use Case Diagram for Enhancing Warehouse Performance at PT. MDA Through the Implementation of 5S, Economic Order Quantity, Safety Stock, and Warehouse Management System. *Engineering, MAthematics and Computer Science Journal* (EMACS), 6(1), 69-78. https://doi.org/10.21512/emacsjournal.v6i1.11204
[68] Lai, J. H., Hou, H., Edwards, D. J., and Yuen, P. L. (2022). An analytic network process model for hospital facilities management performance evaluation. *Facilities*, *40*(5/6), 333-352. https://doi.org/10.1108/F-09-2021-0082
[69] Leończuk, D. (2021). Factors affecting the level of supply chain performance and its dimensions in the context of supply chain adaptability. *Log-Forum*, 17(2). https://doi.org/10.17270/J.LOG.2021.584
[70] Liao, J. (2023). SUSTAINABLE FRESH FOOD COLD SUPPLY CHAIN (CSC).
[71] Liao, J., Tang, J., Vinelli, A., and Xie, R. (2023). A hybrid sustainability performance measurement approach for fresh food cold supply chains. *Journal of Cleaner Production,* 398, 136466. https://doi.org/10.1016/j.jclepro.2023.136466
[72] Liu, Y., Eckert, C., Yannou-Le Bris, G., and Petit, G. (2019). A fuzzy decision tool to evaluate the sustainable performance of suppliers in an agrifood value chain. *Computers and Industrial Engineering*, 127, 196-212. https://doi.org/10.1016/j.cie.2018.12.022
[73] Lusiantoro, L., Yates, N., Mena, C., and Varga, L. (2018). A refined framework of information sharing in perishable product supply chains. *International Journal of Physical Distribution and Logistics Management*, 48(3), 254-283. https://doi.org/10.1108/IJPDLM-08-2017-0250
[74] Masudin, I., Ramadhani, A., Restuputri, D. P., and Amallynda, I. (2021). The effect of traceability system and managerial initiative on Indonesian food cold chain performance: A Covid-19 pandemic perspective. *Global Journal of Flexible Systems Management*, 22(4), 331-356. https://doi.org/10.1007/s40171-021-00281-x
[75] Matthews, A. (2021, November). Contingency plan for ensuring food supply and food security. *In Workshop Report-JRC Conference*, Luxemburgo.
[76] Mecalux. (2025). Cold Storage Warehousing. *Mecalux*. Available at: https://www.mecalux.com/blog/cold-storage-warehousing (Accessed, Jan 20, 2025).
[77] Mohammed, M., Riad, K., and Alqahtani, N. (2022). Design of a smart IoT-based control system for remotely managing cold storage facilities. *Sensors*, 22(13), 4680. https://doi.org/10.3390/s22134680
[78] Mor, R.S., Bhardwaj, A. and Singh, S. (2018), "Benchmarking the interactions among performance indicators in dairy supply chain: An ISM approach", *Benchmarking: An International Journal,* 25 (9), pp. 3858-3881. https://doi.org/10.1108/BIJ-09-2017-0254
[79] Mourral, E., and Lesaffre, C. (2020). Benefits and Challenges of an Automated Storage and Retrieval System: A theoretical study on Food and Pharmaceutical automated storage and retrieval process.
[80] Muravev, D., Hu, H., Zhou, H., and Pamucar, D. (2020). Location optimization of CR express international logistics centers. *Symmetry*, *12*(1), 143. https://doi.org/10.3390/sym12010143
[81] Muthu. S., Jaiswal. A.K. (2013). AVP–RandD, N. T. D. Refrigerant types, issues, trends and future options.
[82] OBERTI, C., and Nannarone, A. (2022). Traceability, transparency, visibility and sustainability in food industry: the role of technology.
[83] Obioma, O. (2016). Servqual Model as Performance Evaluation Instrument for Small and Medium Sized Enterprises (SME): Evidence from Customers in Nigeria. *European Scientific Journal*, 12 (28). https://doi.org/10.19044/esj.2016.v12n28p520
[84] Odun-Ayo, I., Ajayi, O., Akanle, B., and Ahuja, R. (2017, December). An overview of data storage in cloud computing. In 2017 *International Conference on Next Generation Computing and Information Systems (ICNGCIS)* (pp. 29-34). IEEE. https://doi.org/10.1109/ICNGCIS.2017.9
[85] Oró, E., Miró, L., Farid, M. M., Martin, V., and Cabeza, L. F. (2014). Energy management and CO2 mitigation using phase change materials (PCM) for thermal energy storage (TES) in cold storage and transport. *International journal of refrigeration*, 42, 26-35. https://doi.org/10.1016/j.ijrefrig.2014.03.002
[86] Pamučar, D., Vasin, L., and Lukovac, L. (2014). Selection of railway level crossings for investing in security equipment using hybrid DEMATEL-MAIRCA model. *In: Proc. of the XVI International Scientific-Expert Conference on Railways, Serbia*, 89–92.
[87] Pandey, M., Khare, N., and Shrivastava, S. C. (2012). New Aggregation Operator for Triangular Fuzzy Numbers based on the Geometric Means of the Slopes of the L-and R-Membership Functions. *International Journal of Computers and Technology*, *2*(2), 74-76. https://doi.org/10.24297/ijct.v2i2b.2634
[88] Parasuraman, A. P., Zeithaml, V., and Berry, L. (1988). SERVQUAL A Multiple-item Scale for Measuring Consumer Perceptions of Service Quality. *Journal of Retailing*, 64, 12-40.
[89] Patel, B. S., and Sambasivan, M. (2022). A systematic review of the literature on supply chain agility. *Management Research Review*, 45(2), 236-260. https://doi.org/10.1108/MRR-09-2020-0574
[90] Pedro, A. L., Rodolfo, R. V., Arturo, M. H. P., Nazmín, T. G. D., and Antonio, S. J. L. (2023). Cold chain relevance in the food safety of perishable products. *Foods and Raw materials*, 11(1), 116-128. https://doi.org/10.21603/2308-4057-2023-1-559
[91] Peter, T. (2007). Decontamination of cold storage facilities. Packers Newsl.. 89. 5-7.
[92] Qrunfleh, S., and Tarafdar, M. (2014). Supply chain information systems strategy: Impacts on supply chain performance and firm performance. *International journal of production economics*, 147, 340-350. https://doi.org/10.1016/j.ijpe.2012.09.018
[93] Rabbi, M. F., Hasan, M., and Kovács, S. (2021). Food security and transition towards sustainability. *Sustainability*, *13*(22), 12433. https://doi.org/10.3390/su132212433

[94] Raja Suganya, P. V., Devi, T., and Joshita, V. (2024, March). Next-Gen Cold Storage Surveillance Platform. *In Analytics Global Conference* (pp. 3-18). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-75157-8_1
[95] Rajagopal, A. (2010). IMPACT OF QUALITY PROGRAMS ON SUPPLY CHAIN PERFORMANCE. *Global Management Review*, 4(3).
[96] Ramos, E., Coles, P. S., Chavez, M., and Hazen, B. (2022). Measuring agri-food supply chain performance: insights from the Peruvian kiwicha industry. *Benchmarking: An International Journal*, 29(5), 1484-1512. https://doi.org/10.1108/BIJ-10-2020-0544
[97] Rasool, F., Greco, M., and Grimaldi, M. (2022). Digital supply chain performance metrics: a literature review. *Measuring Business Excellence*, 26(1), 23-38. https://doi.org/10.1108/MBE-11-2020-0147
[98] Razak, G. M., Hendry, L. C., and Stevenson, M. (2023). Supply chain traceability: A review of the benefits and its relationship with supply chain resilience. *Production Planning and Control*, 34(11), 1114-1134. https://doi.org/10.1080/09537287.2021.1983661
[99] Richards, G. (2017). *Warehouse management: a complete guide to improving efficiency and minimizing costs in the modern warehouse*. Kogan Page Publishers.
[100] Rodríguez-Escudero, A. I., Camarero-Izquierdo, C., and Redondo-Carretero, M. (2023). Towards profitable customized solutions in small firms: a matter of relationships, modularity and expertise. *Journal of Business and Industrial Marketing*, 38(1), 137-154. https://doi.org/10.1108/JBIM-03-2021-0147
[101] Rogerson, M., and Parry, G. C. (2020). Blockchain: case studies in food supply chain visibility. *Supply Chain Management: An International Journal*, 25(5), 601-614. https://doi.org/10.1108/SCM-08-2019-0300
[102] Saaty,T.L. (1999). *Fundamental of the Analytical Network Process*. University of Pittsburgh, Japan. https://doi.org/10.13033/isahp.y1999.038
[103] Sahoo, S. K., and Goswami, S. S. (2023). A comprehensive review of multiple criteria decision-making (MCDM) Methods: advancements, applications, and future directions. *Decision Making Advances*, *1*(1), 25-48. https://doi.org/10.31181/dma1120237
[104] Sangari, M. S., Razmi, J., and Zolfaghari, S. (2015). Developing a practical evaluation framework for identifying critical factors to achieve supply chain agility. *Measurement*, 62, 205-214. https://doi.org/10.1016/j.measurement.2014.11.002
[105] Shravanthi, A. R., and Mahendran, K. (2018). Relationship and information management activities of cold storage warehouses with its stake-holders: A study in Guntur district of Andhra Pradesh. *Small*, 24950(69.83), 10780.
[106] Siddh, M. M., Soni, G., Jain, R., and Sharma, M. K. (2018). Structural model of perishable food supply chain quality (PFSCQ) to improve sustainable organizational performance. *Benchmarking: An International Journal*, 25(7), 2272-2317. https://doi.org/10.1108/BIJ-01-2017-0003
[107] Singh, R. K., Gunasekaran, A., and Kumar, P. (2018). Third party logistics (3PL) selection for cold chain management: a fuzzy AHP and fuzzy TOPSIS approach. *Annals of Operations Research*, 267, 531-553. https://doi.org/10.1007/s10479-017-2591-3
[108] Singh, R., Thakur, R. K., Kalal, N., Praveen, S., Husain, D., and Prakash, R. (2021). Energy Efficient Design of Cold Storage.
[109] Singh, S., and Rana, R. (2017). Study of consumer perception of digital payment mode. *Journal of internet banking and commerce*, 22(3), 1-14.
[110] Stergiou, F. (2018). Effective management and control of the cold chain by application of time temperature indicators (TTIs) in food packag-ing. *Journal of Food and Clinical Nutrition*, 1(1), 12-15.
[111] Sufiyan, M., Haleem, A., Khan, S., and Khan, M. I. (2019). Evaluating food supply chain performance using hybrid fuzzy MCDM technique. *Sus-tainable production and consumption*, 20, 40-57. https://doi.org/10.1016/j.spc.2019.03.004
[112] Tsang, Y. P., Choy, K. L., Poon, T. C., Ho, G. T. S., Wu, C. H., Lam, H. Y., ... and Ho, H. Y. (2016, November). An IoT-based occupational safety management system in cold storage facilities. In *6th International Workshop of Advanced Manufacturing and Automation* (pp. 7-13). Atlantis Press. https://doi.org/10.2991/iwama-16.2016.2
[113] Ugonna, C. U., Jolaoso, M. A., and Onwualu, A. P. (2015). Tomato value chain in Nigeria: Issues, challenges and strategies. *Journal of Scientific Research and Reports*, 7(7), 501-515. https://doi.org/10.9734/JSRR/2015/16921
[114] UNEP and FAO. 2022. Sustainable Food Cold Chains: Opportunities, Challenges and the Way Forward. Nairobi, UNEP and Rome, *FAO*. https://doi.org/10.4060/cc0923en
[115] Uyen, V. T. N., Ersoy, N., Trung, D. D., & Giang, N. T. P. (2024). Applying MCDM to evaluate benchmark scores in the logistics sector for the period 2021–2023: Application to universities in Vietnam. *Journal of Infrastructure, Policy and Development*, *8*(11), 8942. https://doi.org/10.24294/jipd.v8i11.8942.
[116] WEL Companies. (n.d.). *How to optimize space in a cold storage warehouse*. Retrieved January 19, 2025, from https://www.welcompa-nies.com/blog/how-to-optimize-space-in-a-cold-storage-warehouse/
[117] Yadav, S., Garg, D., and Luthra, S. (2021). Development of IoT based data-driven agriculture supply chain performance measurement frame-work. *Journal of Enterprise Information Management*, 34(1), 292-327. https://doi.org/10.1108/JEIM-11-2019-0369
[118] Ye, F., and Wang, Z. (2013). Effects of information technology alignment and information sharing on supply chain operational perfor-mance. *Computers and Industrial Engineering*, 65(3), 370-377. https://doi.org/10.1016/j.cie.2013.03.012
[119] Yousefi, H., Su, H. M., Imani, S. M., Alkhaldi, K., M. Filipe, C. D., and Didar, T. F. (2019). Intelligent food packaging: A review of smart sensing technologies for monitoring food quality. *ACS sensors*, 4(4), 808-821. https://doi.org/10.1021/acssensors.9b00440
[120] Yu, Z., Jung, D., Park, S., Hu, Y., Huang, K., Rasco, B. A., ... and Chen, J. (2022). Smart traceability for food safety. *Critical Reviews in Food Science and Nutrition,* 62(4), 905-916. https://doi.org/10.1080/10408398.2020.1830262
[121] Yurtseven, C., Ekren, B. Y., and Toy, A. O. (2022). An Overview of Warehouse Operations for Cold Chain. *In Industrial Engineering in the Internet-of-Things World: Selected Papers from the Virtual Global Joint Conference on Industrial Engineering and Its Application Areas, GJCIE 2020*, August 14–15, 2020 (pp. 161-175). Springer International Publishing. https://doi.org/10.1007/978-3-030-76724-2_13
[122] Zak, A. (2015). Triple bottom line concept in theory and practice. *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu*. https://doi.org/10.15611/pn.2015.387.21
[123] Zeggio, F. (2020). E*nvironmentally friendly technologies for energy systems in the cold chain for food* (Master's thesis, Universitat Politècnica de Catalunya).

Appendix I

Holistic Performance Assessment-Cold Storage Service Provider

1. Criterion 1. resilience assessment

Supply Chain Resilience stands out as a critical attribute within supply chain management, determining the ability of the system to not just bounce back from hindering incidents, but also change and adapt accordingly (Atadoga et al., 2024).

1.1. Flexibility (Empowers the Supply Chain to utilize its resources efficiently and effectively towards responding to changing needs and requirements without additional cost, time, and performance losses) (Jansen, 2024)

Measures of Flexibility (Kurien and Qureshi, 2015. Ramos et al., 2022).

- Ability to support minor changes in Capacity (through addition/reduction of number of Refrigeration Units/Rooms) (Jansen, 2024).
- Ability to provide tailored solutions/customized solutions tailored to specific Industry Requirements (Rodríguez-Escudero et al., 2023).

- Availability of Multi-Skilled Work Force (Haleem and Shah, 2015).
- Ability to handle Multiple Product Types (Variety Flexibility)
- Ability to handle Multiple Packaging Sizes (Volume Flexibility) (Jack and Raturi, 2002, Shravanthi and Mahendran, 2018).
- Ability to offer Storage Services for both Short and Long Time Spans (Temporal Flexibility) (Shravanthi and Mahendran, 2018).
- Availability of different temperature zones for product storage (Brzozowska et al., 2016; WEL Companies, n.d.)
- Storage Space equipped with flexible storage options-pallet racking/shelfing for optimal space utilization (Fikiin and Markov, 2014; Khan et al., 2019).
- IT systems capable of handling multiple data formats imported from external sources (Abu-Nahel et al., 2020).
- Ability to implement FIFO systems (Hertog et al., 2014).
- Availability of Blast Freezers for rapid freezing (Hoang and Carson, 2024; Kitinoja, 2013).
- Ability to accommodate various Payment Modes (Singh and Rana, 2017).

1.2. Agility (respond quickly to changing needs and requirements) (patel and sambasivan, 2022)

Measures of Agility (Sangari et al., 2015; Raja Suganya et al., 2024).
- Ability to quickly segregate products in case of ailment identification (Yu et al., 2022).
- Ability to swiftly fine-tune the storage conditions to align with the environmental changes (Aung and Chang, 2014).
- Ability to offer customized storage solutions to the customers (Rodríguez-Escudero et al., 2023).
- Ability to provide multi-temperature storage for customers (Brzozowska et al., 2016; WEL Companies, n.d.).
- Structural Agility- Ability to scale-up and scale-down the infrastructural assets (Kitinoja, 2013; Yurtseven et al., 2022).

1.3. Adaptability (ability of the supply chain to respond effectively and efficiently to changes, disruptions, and the uncertainties within the supply chain environments) (leończuk, 2021)

Measures of Adaptability (Leończuk, 2021).
- With respect to the devastating impact of the Covid-19 pandemic on the supply chains. Has the firm formulated any contingency plans or plausible scenarios to reduce the impact of such occurrences within the future (Matthews, 2021).
- Is your cold storage designed with modular capabilities to scale-up and scale-down the capacities to respond to demand fluctuations (Dzyvak and Vovk, 2023; Jansen, 2024; Yurtseven et al., 2022).
- Do you have an ability to tailor your supply chain operations to deliver additional value to the customers (Rodríguez-Escudero et al., 2023).
- Do you have any standard protocols in the event of power-failure or voltage fluctuations (Such as alternate power sources or voltage regulators) (Aziz et al., 2024, Oró et al., 2014).
- Do you have dynamic control measures in place that instigate automatic interventions, i.e., Optimizing temperature and humidity conditions based on changing environmental factors or product characteristics (Aung and Chang, 2014, Brzozowska et al., 2016; Shravanthi and Mahendran, 2018).
- Do you have advanced analytics based on real-time data in place to foresee any potential issues and initiate corrective measures (Kale and Patil, 2021).
- Do you have secured air-lock systems installed to prevent loss of cold (during product in-flows and out-flows) (Fikiin and Markov, 2014).
- Does your IT system facilitate seamless communication, data sharing with all the key stakeholders in order to promptly reduce issues, foster transparency and trust (Raja Suganya et al., 2024).

1.4. Visibility and traceability (allows a business to monitor its supply chain from end-to-end ensuring that all components are accounted for and that any issues are quickly identified and addressed) (rogerson and parry, 2020; razak et al., 2023)

Measures of Visibility and Traceability
- Optimized Store Layouts for enhanced visibility and traceability of products (Jermsittiparsert et al., 2019).
- Usage of RFID and Barcodes for advanced Inventory Tracking and Management (OBERTI and Nannarone, 2022).
- Availability of TTI's (Time-Temperature Indicators) to provide time-temperature history of the food products in real-time (Anug and Chang, 2022; Brzozowska et al., 2016).
- Availability of Temperature or Environment Data Loggers to record and communicate temperature, humidity, and air composition measurements in real-time (Brzozowska et al., 2016; Pedro et al., 2023; Stergiou, 2018).
- Availability of LED lighting to enhance visibility and enable efficient tracking of products (Füchtenhans et al., 2021)
- Availability of product storage options to prevent over-crowding enabling visibility and efficient tracking of products (Fikiin and Markov, 2014).
- Ability to trace and track products from its origin (Masudin, 2021).

2. Criterion 2. sustainability assessment

Sustainability is the ability of a firm to equally prioritize environmental responsibility, social responsibility, and economic viability (Liao et al., 2023, Kumar et al., 2022, Kumar and Choubey, 2023)

2.1. Environmental sustainability (is the ability of a business to interact with the planet in a responsible manner by using its resources to meet their needs without compromising the needs of the future generations and further to conduct a business in a responsible manner with minimal negative impact on the planet) (kumar et al., 2023, liao et al., 2023)

Measures of Environmental Sustainability (Kumar et al., 2023, Liao et al., 2023, Zeggio, 2020).

- Usage of alternate energy sources to reduce the burden of usage of fossil fuels with high carbon footprints for refrigeration (Kitinoja, 2013).
- Usage of Thermal Energy Storage based on Phase Change Materials (PCM) to avoid excessive dependence on grid power and reduce negative environmental impact.
- Usage of Solid Chemistry Water treatment solutions to keep evaporative condensers and cooling tower surfaces free of corrosion and deposits (Ap Tech Group, 2025).
- Usage of Natural Refrigerants such as Ammonia (R-717), CO2 (R-744), Propane (R-290), and Isobutane (R-600a) in place of hydro-fluro carbons to reduce the environmental damage (Muthu and Jaiswal, 2013; Pedro et al., 2023).
- Cold storage facilities rely heavily on HVAC systems to sustain the optimal environments for storage. Hence, do you have your HVAC systems coupled with Industrial Air Purifiers using UV lamps to remove dust, debris, smoke, airborne contaminants and other infectious agents from HVAC systems, in order to improve the in-door air quality (Bearg, 2019).
- Availability of Rainwater Harvesting Pits to reduce dependence on ground water sources (de Sá Silva et al., 2022).
- Use of proper insulation within the facility to avoid loss of heat/temperature (Kitinoja, 2013; Singh et al., 2021).
- Usage of Vacuum piping networks for drainage (Adler and Zinn, 2021).
- Going paperless for both internal and external communication needs.
- Ability to reuse the pallets and containers used for storage.

2.2. Social sustainability (it refers to business contribution towards social upliftment)

Measures of Social Sustainability (Liao et al., 2023)

- Employability-the firm stands out as an employer- creating and maintaining jobs that are stable, fulfilling, and support employees personal and professional development through elevation of the living standards.
- Acting as an employer promoting diversity and inclusion (equal opportunities, equal pay and eliminating discrimination).
- Engaging in voluntary activities for social benefit.
- Acting as an employer adhering to ethical labour practices (No child Labour).
- Providing a safe work environment free from accidents
- Acting as a business compliant with all of the legal and regulatory requirements for societal wellbeing (Pollution control, noise control etc.)

2.3. Economic sustainability (aims at focusing on finding a balance between economic growth and responsible resource usage)

Measures of Economic Sustainability (Liao et al., 2023, Sufiyan et al., 2019)

- Usage of full warehouse space for economic viability (storage capacity maximization)
- Reduce dependence on grid power through usage of cost-efficient renewable energy sources (Kitinoja, 2013).
- Practice of engaging in keeping the condenser units clean to ensure cost-efficiency through maximum airflows.
- Usage of Auto Doors or Air Curtains for cost-efficiency through effective management of ambient environmental conditions within the facility (Gwynne, 2014).
- Usage of LED lighting to cut down the energy costs (Richards, 2017).
- Engaging in preventive maintenance activities to avoid equipment breakdowns resulting in economic losses (Guo and Tsai, 2019).

2.4. Food security (to ensure the availability of food at all times) (liao, 2023)

Measures of Food Security (Atkins et al., 2018, Liao, 2023, UNEP and FAO, 2022).

- Act as a buffer for food supply-through cold storage-reducing seasonal short falls and post-harvest losses
- Continual Monitoring of storage conditions (temperature and humidity) through sensors for shelf-life enhancement.
- Availability of mechanisms to alert deviations from required storage requirements/conditions.
- Availability of alternative power sources as a back-up to take care of power outages and ensure continuity in cooling.
- Availability of separate storage spaces for storage of different kinds of foods with different storage requirements.
- Effective ventilation and air flow in place to avoid food spoilage.
- Air-quality control checks in place to avoid accumulation of dust, pollutants, and odor.
- Regular cleaning schedules and pest control in place to maintain proper hygiene and avoid food contamination by rodents and insects.
- Infrastructure security measures in place to avoid unauthorized access.
- Scheduled inspections in place to ensure usage of good food handling practices to avoid cross-contamination and spoilage of foods.

3. Criterion 3. digitalization assessment

Deployment of digital tools and technologies to improve management, streamline operations, and enhance visibility. (Gupta et al., 2021, Rasool et al., 2022).

3.1. Information sharing/transparency (voluntary act of making information possessed by one entity available to other entity in an open and honest manner) (ye and wang, 2013)

Measures of Information Sharing/Transparency (Lusiantoro et al., 2018).

- Usage of Digital Dash Boards to display Key Metrics from multiple data sources through tools such as Excel, Power BI, Zoho Analytics etc (Hienen, 2024)
- Real-time data and information access facilitated through centralized ERP systems (Qrunfleh and Tarafdar, 2014)

- Usage of Social-Media platforms for real-time circulation of information (Agnihotri et al., 2022)
- Usage of Collaborative tools such as MS teams, Zoom/Google Meets to share information and knowledge through online meetings.
- Usage of Cloud servers for data storage and easy access of information (Odun-Ayo et al., 2017).
- Possess a dedicated business website to share information with potential customers and engage/retain current customers.

3.2. Data collection (facilitated through digital tools) (yadav et al., 2021)

Measures of Data Collection (AlMulhim, 2021).
- Usage of Bar-Code technology for product tracking and tracing.
- Usage of RFID technology for product tracking and tracing.
- Usage of IoT sensors for real-time measurements of environmental parameters and product characteristics.
- Usage of dedicated Mobile Apps for customer order management.
- Usage of Intelligent Packaging Systems for real-time measurements of environmental parameters and product characteristics (Yousefi et al., 2019)
- Usage of TTI's (Time-Temperature Indicators) to provide time-temperature history of the food products in real-time (Brzozowska et al., 2016).

3.3. Traceability (ability to trace the products history (location, condition, etc.) from its point of origin) (caro et al., 2018)

Measures of Traceability
- Usage of Block-Chain Technology to create a secure and tamper-proof record of all the transactions related to the product from its point of origin (External Traceability).
- Internal Traceability facilitated through ERP systems.
- RFID to aid with the product identification, location tracking, and the condition of the product.
- IoT sensors to track products and provide real-time insights on product characteristics.

3.4. Analytics (usage of mathematics, statistics, and machine learning to find meaningful insights from the data) (cemberci et al., 2024)

Measures of Analytics: please check only the options that are relevant and are available within the Cold Storage Facility.
- Data Analytics facilitated through Excel Spread Sheets.
- Data Analytics facilitated through customized ERP Reports.
- Data Analytics facilitated through advanced analytical tools such as Excel Solver, Power BI, Zoho Analytics etc.
- Data Analytics facilitated through Machine Learning Algorithms for real-time forecasting of food quality based on anticipated changes within environmental conditions.

3.5. Remote management (facilitated through digital tools and technologies) (mohammed et al., 2022)

Measures of Remote Management
- Smart Shelving- Automated shelfing systems that can self-adjust storage conditions with respect to the changes in environmental conditions or product characteristics.
- Cloud platforms that are capable of remotely monitoring the products and send out real-time alerts for interventions (Ivanov et al., 2022).

4. Criterion 4. product quality assessment

Assessing, Monitoring, and Managing the quality of products and processes to safeguard the face value and nutrition value of the foods (Brzozowska et al., 2016; Ramos et al., 2022, Siddh et al., 2018, Sufiyan et al., 2019).

4.1. Tangible/built infrastructural capabilities (equipped with an ability to provide environments for safeguarding the product integrity). (ugonna et al., 2015)

Measures of Tangible/Built Infrastructural Capabilities
- Availability of storage capabilities i.e., rooms, racks, shelfing to accommodate products with diverse characteristics and maintenance environments (Guo and Tsai, 2019; Kitinoja, 2013).
- Availability of HVAC systems with Ammonia cooling units to maintain the ideal temperatures needful for product storage and shelf-life extension (Bearg, 2019).
- Availability of storage units with proper insulation to reduce heat transmission resulting in environmental changes that are not ideal for sustenance of product quality (Kitinoja, 2013; Singh et al., 2021).
- Storage spaces, racks, shelves, properly laid out to enhance the visual display of products facilitating reduction of pathogenic contamination, dehydration, excessive ripening and discoloration.
- Availability of proper lighting for enhanced visibility (Füchtenhans et al., 2021).
- Availability of proper handling equipment, conveyors, ASRS systems to reduce handling damages (Brzozowska et al., 2016; Khan et al., 2019; Mourral and Lesaffre, 2020).
- Availability of blast freezing to reduce the time zones for bacterial contamination (Abaasa, 2023, Mourral and Lesaffre, 2020).

4.2. Technical capabilities (how the service facility uses technology to sustain the product quality) (pedro et al., 2023)

Measures of Technical Capabilities (AlMulhim, 2021; Rasool et al., 2022).

- Availability of Bar-Code or RFID scanners/tags to convene tracking and tracing of basic product characteristics.
- Availability of IoT sensors for real-time measurements of environmental parameters and product characteristics.
- Availability of TTI's (Time-Temperature Indicators) to provide time-temperature history of the food products in real-time (Brzozowska et al., 2016).
- Availability of Smart Shelving- Automated shelfing systems that can self-adjust storage conditions with respect to the changes in environmental conditions or product characteristics.
- Deployment of cloud-based platforms -for remote monitoring of product characteristics and capable of sending out alerts to primary stakeholders facilitating immediate interventions (Ivanov et al., 2022).
- Availability of digital dash boards for display of product characteristics/process parameters.

4.3. Quality tools and procedures (facilitate identification of problems (variability/defects), root causes, and foster continuous improvements) (rajagopal, 2010)

Measures of Quality Tools and Procedures

- Usage of the Seven QC Tools for Continual Improvements.
- Usage of Statistical Process Control Charts to track and monitor Product attributes/Process characteristics.
- Evidence of a Kaizen Log for Continual Improvements.
- Deployment of Six Sigma Projects for Process Improvements
- Visual display of Quality Assurance Plans and Procedures.
- Usage of IQC, In-Process QC and Final QC for Quality Assurance.
- Effective Calibration Management to ensure reliable measurements.

4.4. Analytical capabilities (ability to transform data into information fostering real-time decision making)

Measures of Analytical Capabilities: please check only the options that are relevant and are available within the Cold Storage Facility (Alrae, 2024).

- Ability to draw insights through deployment of basic 7 QC tools for quality enhancement/sustenance.
- Ability to use Statistical Process Control Charts to track process characteristics and product attributes.
- Ability to use Big Data Tools to segregate products based on quality characteristics/attributes.
- Ability to deploy Machine Learning algorithms for real-time forecasting of food quality based on anticipated changes within environmental conditions.

4.5. Knowledge capabilities (are the sum of knowledge assets of an organization)

Measures of Knowledge Capabilities (Haleem and Shah, 2015).

- Employees ability to handle products with variant/diverse storage requirements and with specialized knowledge on the effect of temperature on product characteristics.
- Employees ability to deploy available technologies to track and trace products, their characteristics, and environmental conditions towards safeguarding the quality of products.
- Employees ability to handle storage equipment's within the set target limits for product sustenance.
- Employees ability to deploy handling equipment's to avoid mishandling of products (Mourral and Lesaffre, 2020).
- Employees ability to spot visible product ailments to avoid product contamination.
- Employees ability to use various quality tools for product quality sustenance.
- Evidence of regular awareness/training sessions on product quality requirements/technology usage (Brzozowska et al., 2016; Guo and Tsai, 2019; Kitinoja, 2013).

4.6. Certifications (an assurance from a certified/regulatory body that the system can meet the desired requirements) (joshi et al., 2024)

Measures of Certifications

- ISO 9001 Compliance to ensure that the cold storage facility meets the highest quality standards of quality and reliability (Pedro et al., 2023).
- FSSAI/International standard for food safety: compliance with the Food Safety and Standards Authority of India/International Body, in terms of hygiene and basic quality standards ensuring the safety of foods for consumption (Sustenance of the Nutrition Value).

5. Criterion 5. customer service quality assessment

To ensure customer delight through tangibility, reliability, responsiveness, assurance, and empathy from the service delivery (Chartsutthi et al., 2024; Ramos et al., 2022, Sufiyan et al., 2019).

5.1. Tangibility (visible aspects of a business that are appealing to a customer)

Measures of Tangibility

- A clean and organized ambience of the cold storage facility (Mecalux, 2025).
- Informative displays across the floor and storage areas.
- Well-marked aisles designated for people/product movement.
- A centralized help desk for information assistance.

- Store Employees adherence to PPE requirements (Charles, 2020).
- Clear segregation between storage of product lines and other items.

5.2. Reliability (ability of the system to deliver the intended function consistently) (singh et al., 2018)

Measures of Reliability

- Evidence of the existence of loyal/repeated customers.
- Availability of employees with specialist knowledge and skills in several areas, including general awareness and knowledge of the effects of temperature on food products, product specific storage requirements, good practices in the handling and packaging of food products, skills required for the operation of cooling technologies, as well as business and supply chain management and logistics (Guo and Tsai, 2019; Kafetzopoulos et al., 2020)
- Availability of Equipment for safe handling and storage of products (Brzozowska et al., 2016; Khan et al., 2019; Mourral and Lesaffre, 2020).
- Availability of comprehensive records of temperature logs, and equipment maintenance records (Brzozowska et al., 2016; Guo and Tsai, 2019).
- Adherence to insulation, sanitation, and pest control measures (Kitinoja, 2013; Peter, 2007).
- FSSAI/Other International Standard for Food Safety Compliance (Joshi et al., 2024).
- Usage of control charts to monitor and control the process/equipment reliability (Rajagopal, 2010).
- Effective calibration management to ensure measuring equipment reliability (Brzozowska et al., 2016; Guo and Tsai, 2019).

5.3. Responsiveness (ability to swiftly act on customer needs) (guo and tsai, 2019)

Measures of Responsiveness

- A dedicated App to swiftly take customer orders/respond to customer queries.
- An Instagram/face book page to convene regular interaction with the customers.
- An EDI interface to share product related data with customer facilitated through the centralized ERP systems.
- A dedicated website with chatbot facility to swiftly respond to customer queries.
- Centralized location of the facility to quickly respond to immediate market needs for food preservation (Shravanthi and Mahendran, 2018).

5.4. Assurance (providing confidence with regards to rightly meeting the customer needs)

Measures of Assurance

- Certifications ISO 9001, FSSAI/other international food Safety Standards (Joshi et al., 2024; Pedro et al., 2023).
- Well documented quality assurance plans for safe handling of different products (Boonsupthip et al., 2015)
- Training records ascertaining product knowledge, analytical, technical capabilities of the employees (Brzozowska et al., 2016; Guo and Tsai, 2019; Kitinoja, 2013).
- Availability of advanced monitoring and control systems to enable controlled storage environments for products with different storage requirements (Anug and Chang, 2022; Brzozowska et al., 2016).
- Proper cleaning and sanitation in place to avoid contamination and bacterial growth (Peter, 2007).
- Proper ventilation in place to remove excess moisture (Bishnoi and Aharwal, 2024).
- State of art security systems in place to prevent product theft (Chihana et al., 2018).
- Fire safety measures in place to avoid fire accidents (Kocksis et al., 2015).
- Usage of control charts to monitor and control the process performance/product attributes (Rajagopal, 2010).
- Effective calibration management in place for assurance of measurements (Guo and Tsai, 2019).
- Competitive pricing in place that aligns with market pricing (Shravanthi and Mahendran, 2018).

5.5. Empathy (an ability to understand other persons requirements and respond aptly to fulfil their needs)

Measures of Empathy (Kitinoja, 2013)

- Product Ownership (As long as the product is held for storage within the facility, the storage facility takes complete ownership of safeguarding the quality and reducing the risk of product damage by optimally managing the needful storage environments).
- Product Marketability (Uphold the product face and nutrition value for enhanced product marketability)
- Streamlined communication with the customers through dedicated apps, social-media pages, engaging web portals by sharing the product vital information in real-time.
- Evidence of initiating immediate interventions on behalf of customers for safeguarding the quality of products.
- Predict food quality parameters in response to anticipated environmental changes and adjust product storage conditions accordingly to safeguard product quality.

6. Criterion 6. safety assessment

Safe handling of foods to avoid food-borne illness and provide a workplace free of recognized hazards for all the employees.

6.1. Product safety (ensuring that food products are not contaminated with any infectious diseases)

Measures of Product Safety

- Usage of proper PPE to handle the products (Charles, 2020).

- Usage of appropriate handling equipment's and storage containers to avoid product damage and contamination (Brzozowska et al., 2016; Khan et al., 2019; Mourral and Lesaffre, 2020).
- Display of procedures for safe handling of products
- Display of cleaning schedules and strict adherence to the cleaning schedules to maintain hygienic storage environments.
- Display of equipment maintenance schedules and strict adherence to the schedules to avoid product damage resulting from equipment malfunctioning (Guo and Tsai, 2019).
- Availability of storage facilities to convene product segregation and storage (Fikiin and Markov, 2014; Khan et al., 2019).
- Chemicals and any other non-edible material storage are well isolated from the product storage areas.
- Designated walkways and aisles for safe handling of products.
- Availability of safety alarms to send out alerts on temperature deviations (Ivanov et al., 2022).
- Availability of alternate power sources to handle power failures (Aziz et al., 2024, Oró et al., 2014).
- Availability of proper ventilation to avoid product contamination (Bishnoi and Aharwal, 2024).
- Availability of proper drainage systems to avoid stagnant water pools attracting microbial contamination (Adler and Zinn, 2021).
- Ability to facilitate FIFO systems to avoid product spoilage (Hertog et al., 2014).
- State of art security systems in place to avoid product theft (Chihana et al., 2018; Shravanthi and Mahendran, 2018).

6.2. Certifications (an assurance from a certified/regulatory body that the system is capable of meeting the desired requirements)

Measures of Certifications: please check only the options that are relevant and are available within the Cold Storage Facility.

- FSSAI/International standard for food safety: compliance with the Food Safety and Standards Authority of India/International Body, in terms of hygiene and basic quality standards ensuring the safety of foods for consumption (Joshi et al., 2024).
- Compliant with the IFS certification-a series of international standards that assess how well products and processes meet the food safety and quality requirements (Brzozowska et al., 2016).
- Compliant with the 5S certification-that recognizes and certifies organizational implementation of the 5S methodology that fosters high quality housekeeping and waste control (Kurniawan et al., 2024).
- Compliant with the ISO 45001-OHSAS certification in order to safeguard the health and safety within the workplace (Anttonen et al., 2009).

6.3. People safety (to safeguard the health and well-being of the people working within the facility). (tsang et al., 2016)

Measures of People Safety: please check only the options that are relevant and are available within the Cold Storage Facility.

- Usage of Right PPE (Charles, 2020).
- Proper Ventilation (Bishnoi and Aharwal, 2024).
- Availability of displays and instruction manuals for the right usage of Equipment's, Tools and Storage Spaces (Brzozowska et al., 2016; Mourral and Lesaffre, 2020).
- Proper marking of Exits and designated safe assembly zones (Fikiin and Markov, 2014).
- Proper lighting to avoid slip and trip hazards (Füchtenhans et al., 2021)
- Designated storage locations for fire safety equipment’s.
- Flammables like insulation materials and refrigerants are stored within designated locations to avoid contact with foods.
- Assigned storage locations for chemicals and MSDS displayed for safe usage of chemicals.
- Adherence to cleaning schedules to maintain proper hygiene within the storage areas (Garg et al., 2021).
- Usage of non-slippery mats within wet areas.
- Proper draining to avoid water pooling (Adler and Zinn, 2021).
- Adherence to equipment maintenance schedules to avoid equipment malfunctions posing a threat to personnel safety (Guo and Tsai, 2019; Kitinoja, 2013).
- Evidence of regular awareness sessions on safety measures (Hofstra et al., 2018)