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Safety Over Cost: Prioritizing Cold Chain Performance to Mitigate Post-Harvest Food Loss in Tropical Emerging Markets

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Data availability

Data will be made available on request

Declarations

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Ethical Considerations: This study was conducted in accordance with established ethical guidelines for social science research. All participants provided informed consent after being fully briefed on the study's purpose and their rights as respondents. The survey was completely anonymous, with no collection of personally identifiable information. Participants were informed that their participation was voluntary and that they could withdraw at any time without consequence.

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Abstract

Temperature integrity in tropical developing markets is a serious operational problem due to high ambient temperatures and humidity, which lead to an exponential increase in post-harvest food loss and spoilage risks. While conventional supply chain paradigms prioritize short-term cost minimization, this study aims to establish an empirical multi-criteria decision-making (MCDM) framework to prioritize operational mechanisms that safeguard food integrity in tropical cold chain ecosystems. Grounded in the Resource-Based View (RBV) and Supply Chain Risk Management (SCRM) and presents quantified expert agreement throughout the entire distribution network of the Malaysian frozen food industry. A purposive sample of 20 senior industry experts was selected to collect pairwise comparison data, and synthesized following consistency checking of the experts' judgments using the Consistency Ratio (CR < 0.10). The empirical results indicate that the operational criterion with the greatest weight is TC (0.60), followed by SF (0.20), TE (0.14) and CO (0.06). At the sub-criteria level, the most critical driver is technology integration (TC1, global weight 0.44), followed by Efficient Route Planning (TE4, global weight 0.13), Inventory Rotation Techniques (SF8, global weight 0.12) and Real-Time Monitoring (TC2, global weight 0.10). Conversely, global priority sub-criteria are the direct cost-optimization sub-criteria at the bottom rank. Theoretically, these findings demonstrate that in tropical emerging markets, financial cost optimization is a strictly constrained secondary boundary condition secondary to non-negotiable food safety imperatives. Furthermore, it shows that digital telemetry drives operational resilience against thermal degradation. Practically, this study provides policymakers and food safety authorities with a validated roadmap to target public subsidies and private investments toward IoT-enabled telemetry, automated warehousing (AS/RS), and dynamic route optimization to reduce post-harvest waste and enhance national food security.

Keywords: Cold chain logistics; Food safety governance; Post-harvest food loss; Analytical Hierarchy Process (AHP); Supply Chain Risk Management; Tropical food security.

1. Introduction

The rapid increase in urbanization, increasing disposable income and changing consumer food preferences in Southeast Asian countries have contributed to the exponential growth of the tropical frozen food sector [1]. In Malaysian, the frozen food industry is undergoing a period of significant transformation due to rapid urbanization, rising non-refundable incomes, and evolving consumer lifestyles [2]. Market analysts project that the sector will surpass USD 800 million in value within the next five years, supported by a compound annual growth rate exceeding 7% [3]. While traditionally protected in seafood exports, the industry is now diversifying into a broader array of products including organic soups, protein bars, and frozen fruits and vegetables to meet shifting consumer preferences for convenience and healthier options [1, 4]. This expansion is further accelerated by the Malaysian government's active promotion of food safety standards and the chilled-and-frozen food concept, which has strengthened consumer confidence and market growth [5]. However, this promising growth path simultaneously exposes a critical weakness: the existing distribution infrastructure is struggling to keep pace with increasing demand and product complexity. Malaysia's geographically dispersed population and the still developing frozen food distribution channel infrastructure create unique distribution challenges [3]. For frozen food businesses, the core operational challenge lies in maintaining rigorous temperature control throughout the distribution channel, a non-negotiable requirement for preserving food safety and quality [6] while simultaneously managing transport efficiency, storage capacity, and cost optimization [7]. In tropical, developing market environments like Malaysia, maintaining unbroken thermal integrity (typically between −18 °C and −24 °C) represents a non-negotiable operational baseline can result in spoilage, significant economic losses, and a decline in consumer trust [6 - 8].

Despite the importance of cold chain continuity, existing supply chain literature is also scattered and often perceives logistics as a mere business transaction, instead of a critical measure for the protection of post-harvest food losses. In hot and humid developing countries such as Malaysia, long periods of exposure to environmental heat and heavy traffic delays during food transportation cause high post-harvest food losses, huge economic losses, and public health problems due to the speed at which micro-organisms multiply. Most of the theoretical models that exist so far are mainly for single optimization problems such as vehicle routing algorithms [9] or warehouse layout designs [10], where the direct minimization of financial costs is the goal function. In tropical regions, the cost-first approach does not work because any short-term cost saving can lead to catastrophic food spoilage and food safety problems in an exponential way. Thus, an integrative, empirical decision-making framework, which assesses operational trade-offs to safeguard food availability and its quality, is needed in an urgent manner.

This study aims to fill these urgent gaps by examining the dynamic balance and prioritisation of conflicting operational pressures among cold chain actors to reduce food losses. Specifically, this research answers three core research questions:

RQ1: How can a multi-dimensional criteria hierarchy, including Temperature Control (TC), Transport Efficiency (TE), Storage Facility (SF), and Cost Optimization (CO), be demonstrated and structured to address the food preservation constraints of tropical cold chain distribution?

RQ2: What are the priority weights of the twelve operational sub-criteria for local and global levels within the Malaysian frozen food distribution network when expert consensus is synthesised with the Analytic Hierarchy Process (AHP)?

RQ3: What are the empirical trade-offs between temperature compliance and financial optimization challenge traditional trade-off logistics paradigms to support regional food security in tropical markets

This study employs the Analytic Hierarchy Process (AHP), a methodology well-suited for structuring complex, multi-attribute decision problems [11]. The AHP approach is particularly effective in cold chain research because it mathematically synthesizes qualitative expert judgments into objective

priority weights while rigorously verifying judgment consistency [12]. The empirical methodology was executed across three distinct operational phases, beginning with hierarchy structuring based on an extensive literature review and preliminary expert validation. Within this three-level hierarchy, Level 1 defines the overarching objective of prioritizing cold chain performance drivers, Level 2 incorporates four primary criteria (Temperature Control, Transport Efficiency, Storage Facility, Cost Optimization), and Level 3 comprises twelve operational sub-criteria.

This study contributes to the literature in the field of supply chains from three perspectives. First, the combination of the Resource-Based View (RBV) and Supply Chain Risk Management (SCRM) as an empirical study shows that financial cost minimization is not a key driver of operational achievement but is instead a strict boundary condition in the second order. The framework opens up VRIN (Valuable, Rare, Inimitable, Non-substitutable) capabilities in tropical logistics and demonstrates that digital capabilities like real-time telemetry and dynamic temperature analytics are table stakes, while the real challenge lies in higher order capabilities. Second, the research provides both a contextual and an empirical level of precision that is empirically validated, and it is a model specifically tailored to the extreme climatic, structural and regulatory friction in tropical developing markets rather than generic cold chain versions that are built for temperate or advanced economies. Finally, the research results have significant strategic and policy implications with a decision roadmap for industry leaders and policymakers. It outlines exactly where capital expenditures (CapEx) will be redirected away from fleet expansion and toward IoT-based telemetry, automated storage and retrieval systems (AS/RS) and dynamic rerouting to increase the resilience of the cold chain.

After the structural establishment, section 2 comprised data collection and pairwise comparisons, in which primary data were collected from a purposive sample of 20 senior cold chain experts (including heads of supply chain operations, transport and logistics directors, and industry analysts) who filled out structured questionnaires using Saaty's fundamental scale of 1 to 9 to determine the relative importance of the criteria and sub-criteria. Finally, in Phase 3, the mathematical synthesis and consistency testing were

carried out by building pairwise comparison matrices, computing local priority vectors (eigenvectors) and maximum eigenvalues (Lambda) to determine Consistency Indexes (CI) and Consistency Ratios (CR) and discarding inconsistent judgments according to Saaty's strict threshold (CR) < 0.10) before synthesizing and arriving at final global priority weights.

2. Theoretical foundation and literature review

This study adopted the Resource-Based View (RBV) [13] and Supply Chain Risk Management (SCRM) [14] theory as the dual underpinning theories to evaluate and prioritize the cold chain performance criteria in frozen food distribution in Malaysia. The RBV theory is based on the assumption that valuable, rare, inimitable, and non-substitutable (VRIN) internal resources and high-order organizational capabilities enable sustainable operational performance [13]. Long-term competitive protection comes from the combination of physical assets, like temperature-controlled cold storage facilities and reefer transport fleets, and digital capabilities, including those enabled by technology [15]. From this perspective, advanced technology integration, real-time thermal monitoring, intelligent route planning, and blockchain-based traceability are all key capabilities that can help streamline logistics in tropical market scenarios. A cold chain logistics distribution optimization model : Beijing-Tianjin-Hebei region low-carbon site selection [16]. CRM theory fills the gaps of RBV theory's internal capability emphasis by offering a framework for identifying, assessing, and mitigating operational vulnerabilities in complex supply networks [14]. Logistics for frozen foods in tropical developing areas are generally exposed to greater environmental conditions, the risk of transit delays, and thermal abuse risks [17]. SCRM assumes that operational resilience relies on the ability to proactively mitigate risks, with the pillars of temperature control (TC) and storage facilities (SF) as key components of the defensive strategy aiming to minimize microbiological contamination and financial losses [6, 18]. In addition, SCRM emphasizes the trade-off between cost optimization (CO) and risk avoidance, as CO can lead to short-term savings in operating costs at the expense of the high costs of failure that may occur downstream, in terms of product recalls and brand damage [19]. When combined with SCRM, RBV offers a comprehensive theoretical lens: RBV

allows us to understand how resources can be allocated internally and how digital capability could be deployed to maximize the operational efficiency, and SCRM rationalizes why thermal compliance and food safety assurance should be a mathematical consideration which is superior to the direct cost minimization objective for a tropical cold chain.

2.1. Temperature control in tropical cold chain

Continuous thermal stability is the primary requirement to adhere to in tropical cold chains that directly influences product safety, quality maintenance and commercial shelf life [17]. The cold chain standards state that all frozen foods should stay within the strict range of −18 °C to −24 °C, as unmitigated excursions outside the temperature range will accelerate microbial growth and cause the degradation of food and financial loss [18]. While the installation of sensor networks and real-time monitoring of the temperature can enhance visibility [16], it is difficult to maintain uninterrupted thermal conditions throughout the tropical distribution channels under high ambient temperature and humidity [20]. Advanced deployments like RFID, IoT architectures and digital twins improve traceability [21], while thermal packaging protects against heat spikes in the environment over the short term [8]. Due to the unequal air distribution in transport units, however, the temperature in the transport unit varies, especially in the top corners, thus exposing cargo to heat abuse [22, 23]. This is compounded by the fact that operational bottlenecks in loading and unloading are also present [24]. Therefore, an integrated cross-nodal temperature governance framework is needed to ensure food integrity, away from the current individual monitoring system [25, 26].

2.2. Transport efficiency and dynamic routing

Malaysia's frozen food industry, transport efficiency directly determines delivery speed, product safety, and cost control. Efficient route planning minimizes travel time, fuel use, and temperature exposure [27]. Optimization models that include transportation, refrigeration, and cargo damage costs are essential for balancing efficiency with food quality [28, 29]. Without dynamic scheduling and real-time traffic adjustments, delays become unavoidable [30]. Vehicle condition matters equally: proper insulation and

refrigeration capacity are non-negotiable for frozen food [15]. Every stage from manufacturing to final delivery must maintain the distribution chain [8]. Consumer behavior also poses a risk, as many of them are reluctant to use insulated bags during home transport, causing partial defrosting [31]. Therefore, manufacturers should provide suitable packaging to mitigate this gap. Seamless information sharing across the supply chain further improves efficiency. Real-time data on inventory, orders, and weather enables proactive route adjustments [16] . Collaborative platforms between producers, distributors, and retailers minimize delays and ensure on-time deliveries at optimal temperatures [32]. A cold chain logistics distribution optimization model

2.3. Storage infrastructure and digital traceability

Storage facilities must maintain strict temperature-controlled environments to preserve product integrity [33]. Even brief temperature deviations compromise safety [34], and improper humidity leads to dehydration or freezer burn [35]. Efficient warehouse practices directly affect transport efficiency: optimized layouts and reduced handling times speed up loading [36]. Proper pre-cooling before transport minimizes temperature fluctuations [37]. Frozen food distribution channel management strategies, including warehouse design and inventory control, are essential [38]. FIFO rotation techniques prevent temperature abuse, while automated storage systems improve consistency. Blockchain technology offers real-time traceability of temperature and inventory, enabling proactive spoilage prevention [39]. Malaysian frozen food firms increasingly rely on IoT and digital tools for labeling, traceability, and food safety [18, 40]. Without a robust storage infrastructure, even the best transport logistics cannot guarantee product quality. Therefore, investment in advanced refrigeration, automated systems, and blockchain integration is not optional but necessary for Malaysia's frozen food distribution chain resilience.

2.4. Cost optimization and quality compliance

Transportation costs dominate frozen food logistics, yet cost optimization often ranks below quality control in Malaysia's industry [17]. Route optimization and backhaul strategies can reduce expenses but require advanced software or third-party partnerships, and fuel prices limit their effectiveness [41].

Storage-side measures offer clearer returns: high-bay racking increases capacity [42], strategic slotting cuts labor [43], and high-speed doors with better insulation save energy [44]. Warehouse management systems (WMS) optimize picking and inventory visibility [45]. Just-in-time inventory reduces spoilage, and ABC classification focuses resources on high-value items [46]**.** Telematics enable dynamic route adjustments and fuel savings (Miao et al., 2018), while real-time temperature sensors minimize waste [47]. Blockchain further cuts recall costs through traceability and automates payments via smart contracts [19]. Information sharing across the supply chain enhances collaboration [39, 48]. Ultimately, for Malaysian frozen food firms, cost optimization must be pursued without compromising temperature control or transport reliability.

3. Analytical hierarchy process (AHP)

The AHP was developed in 1971 by Professor Thomas L. Saaty from the University of Pittsburgh. The AHP offers a structured approach to decision-making. This method leverages principles from mathematics and psychology to facilitate the organization and evaluation of complex judgments. The AHP is a strategic methodology that effectively combines subjective decision-maker judgments with objective logical thinking. This is achieved by leveraging the expertise and knowledge of professionals [12]. This decision-making framework influences the principles and techniques of the AHP, a prominent method within the field of MCDM [49]. In addition, the AHP can be extended to an Analytical Network Method (ANM) to immediately assess the overall performance of several alternatives [50]. The AHP framework captures complex decisions through three core principles. First, it structures the problem hierarchically, breaking it down into interconnected components that contribute to the overall goal. This improves understanding of the entire system. Second, it prioritizes elements by comparing them in pairs based on specific criteria. Finally, it ensures logical consistency by grouping elements and ranking them according to a defined criterion. This structured approach, along with the clear visual representation of goals, criteria, and alternatives, makes AHP a powerful tool for decision-making. A key strength of AHP is its adaptability to various situations. The model can be tailored to specific problems, needs, and the

decision-maker's expertise, judgment, and preferences, effectively addressing the historical challenge of balancing subjective and objective assessments [11]. The AHP framework for this study is illustrated in Fig. 1.

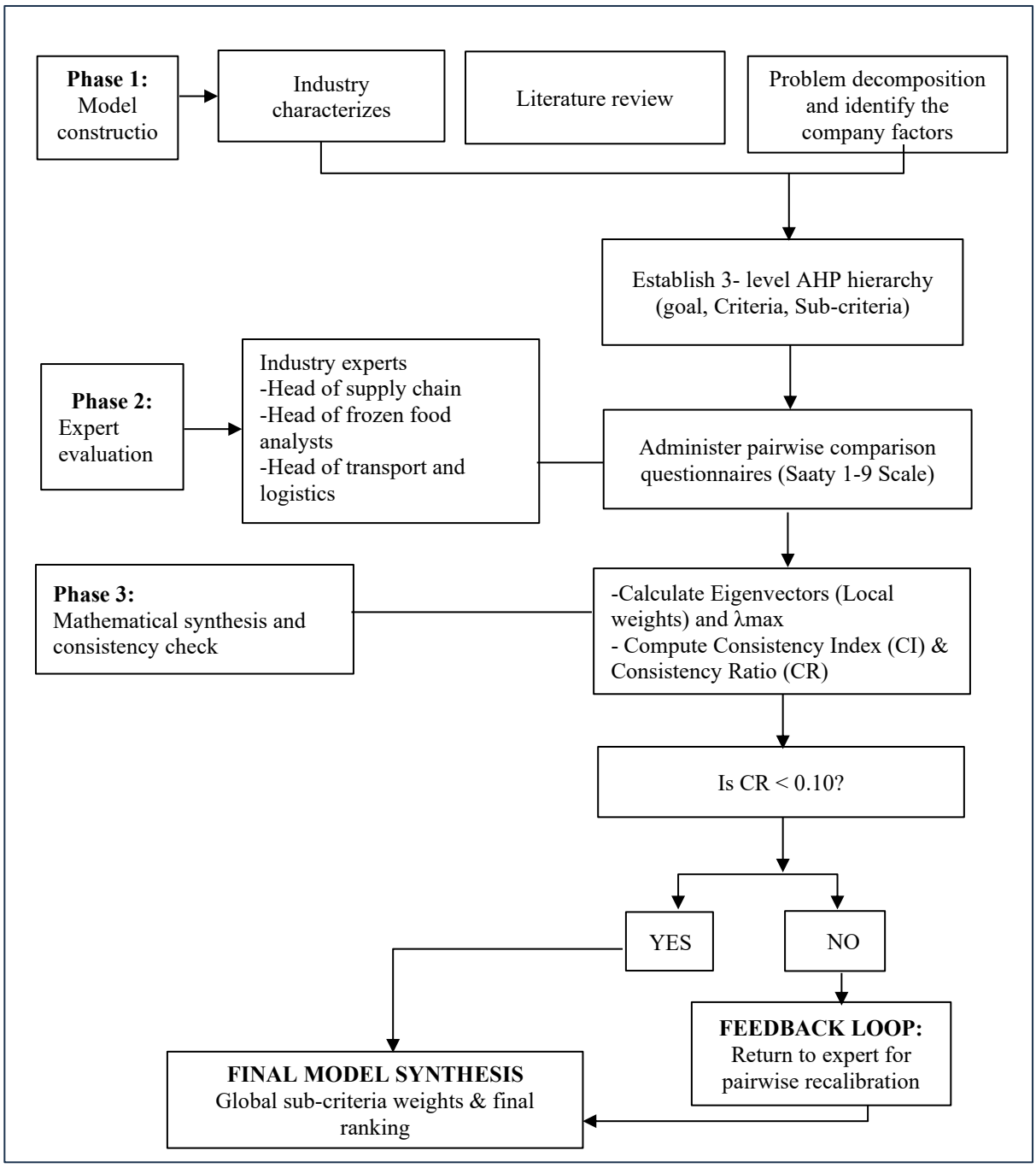


Fig. 1 The operational framework of the study

The operational framework of this study consists of three different phases but is iterative in Fig. 1. Phase 1 decomposes the problem and sets up the initial decision hierarchy in the form of an in-depth literature search and initial expert validation. In Phase 2, the expert panel conducts empirical data collection, in which the expert panel will assess the criteria and sub-criteria using Saaty's 1-9 scale. The mathematical synthesis and consistency testing are carried out in Phase 3. In Phase 3, the decision node ("CR"<0.10), as shown in Figure 1. If the value of the comparison matrix is achieved within this limit, then the priority weights are accepted, and they are synthesized to the final decision model. However, when "CR"≥0.10, the matrix is sent back to Phase 2 for expert recalibration to maintain the integrity and mathematical validity of the empirical outcomes. The following are the specific steps involved in problem-solving using hierarchical analysis:

Step 1: Problem decomposition and identification of the influential factors

A clear understanding of the problem's framework is essential before conducting an AHP. This initial grasp of the system allows us to define the decision's purpose and direction, ultimately facilitating the hierarchical breakdown of influencing factors. Identifying influential factors can be achieved through two methods: group brainstorming or the Delphi Technique. Brainstorming sessions involve focused discussions among key stakeholders, potentially incorporating insights from experts, researchers, and policymakers with specialized knowledge. This comprehensive approach ensures that all relevant perspectives are considered, leading to a thorough enumeration of factors impacting the decision.

Step 2: Building the pairwise comparison matrix

After establishing the hierarchical framework, we create a questionnaire to assess the relative importance of elements within the hierarchy. This involves comparing each factor at a given level with those in the level above, considering their influence on the overall decision. The questionnaire uses a scale of 1 to 9, where evaluators independently assign ratings based on their judgment of each factor's significance. By quantifying these pairwise comparisons, we create a matrix that allows us to calculate eigenvalues and eigenvectors, which will be used to assess consistency in the judgments.

Step 3: Assessing consistency and calculating weights

The AHP method helps us verify the consistency of our judgments within the pairwise comparison matrix. Inconsistent judgments can lead to unreliable results. We calculate eigenvalues and eigenvectors from the matrix. Eigenvectors represent the relative weights (priorities) of each factor within its level. Eigenvalues help assess consistency. A consistency ratio (CR) is calculated based on the eigenvalues. This CR indicates how much the judgments deviate from perfect consistency (where a factor is always compared to itself as equally important). Acceptable CR values are typically below 0.1. Based on the CR, we may need to revisit and refine the pairwise comparisons to improve consistency. Ultimately, by combining the weights across all levels, we arrive at the overall priority of the lowest-level elements in the hierarchy. This information guides the decision-maker towards a well-informed and rational conclusion.

4. Methodology

4.1. Questionnaire instruments

This study primarily employed research instruments encompassing questionnaire instructions, background information, and AHP questionnaires. The instructions were developed based on a comprehensive literature review and expert input from the transportation and logistics field. This study has selected four distribution channel factors that are appropriate for the frozen food industry due to the nature of the products. Thus, the selected distribution channel factors for this industry product are temperature control, transport efficiency, storage facility, and cost optimization. Under the four main factors (criteria), twelve sub-criteria are considered that play an important role in developing the efficiency of the cold chain Performance in frozen food distribution in Table 1.

Table 1 Criteria and description for the cold chain frozen food distribution

No.	Main criteria	Sub-criteria	Authors
1	Temperature Control (TC)	TC1-Technology integration TC2- Monitoring TC3-Packaging integrity	[18] [51] [52]
2	Transport Efficiency (TE)	TE4-Efficient route planning TE5-Vehicle conditions TE6- Collaboration and information sharing	[53] [15] [54]
3	Storage Facility (SF)	SF7- Consistent and accurate temperatures SF8- Inventory rotation techniques SF9-Block chain integration	[55] [56] [57]
4	Cost Optimization (CO)	CO10- Optimal delivery route CO-11- Warehouse management CO-12- Fleet management Software	[58] [59], [60] [61]

4.2. Expert panel selection, demographics, and bias management

A purposive sampling approach was used to select a special panel of expert respondents to ensure that the pairwise judgments were rigorous and representative. In a Multi-Criteria Decision-Making (MCDM) approach that uses the Analytic Hierarchy Process (AHP), the number of criteria and experts are more important than the number of samples, while a panel of 10 to 20 expert respondents is largely accepted as providing good mathematical consensus without inducing noise [11]. As such, a panel comprising 20 senior industry experts and academic specialists across the cold chain of frozen food in Malaysia was set up to assess the decision hierarchy. Selection criteria included having at least seven years of direct experience in operational and/or managerial work in cold supply chain management, temperature-controlled logistics and/or food safety policy. The final panel consisted of 25% supply chain directors, 30% cold chain transport and fleet operations managers, 25% heads of warehouse and cold storage facilities and 20% senior frozen food analysts and academics. As a group, the panel had an average of 12.4 years of experience working in the frozen food logistics industry. The industry participants were carefully selected to reflect a balanced cross-section of key stakeholders in the frozen food industry in Malaysia, comprising major frozen food manufacturing companies (35%), third party cold logistics

providers (30%), retail hypermarket chains (20%) and academic research institutions specializing in SCM (15%), as shown in Table 2.

Table 2 Demographic profile and organizational background of the expert panel (N = 20)

Category	Sub-category	Frequency (n)	Percentage (%)
Professional Role	Cold Chain Transport & Fleet Operations Heads	6	30
	Supply Chain Directors / Executives	5	25
	Warehouse & Cold Storage Facility Managers	5	25
	Senior Frozen Food Analysts / Academics	4	20
Years of Experience	7-10 Years	7	35
	11-15 Years	9	45
	15> Years	4	20
Types of Organization	Frozen Food Manufacturing Enterprises	7	35
	Third-Party Logistics (3PL) Cold Chain Provider	6	30
	Retail & Hypermarket Supply Chain Divisions	4	20
	Academic & Research Institutions	3	15

A multi-step survey administration protocol was used to reduce potential response bias (dominant actor influence, halo effects, and survey fatigue). Secondly, structured pairwise comparison questionnaires were completed in one-to-one sessions either face-to-face or using structured video, so that each expert's judgments were independent and not affected by group dynamics. Second, a detailed briefing document detailing Saaty's 1-9 fundamental scale was given before the evaluation to reduce the cognitive load in the process and to anchor subjective definitions of the scale. Third, during the administration of the questionnaire, real-time consistency checks were performed: if the Consistency Ratio ("CR") obtained from an expert's preliminary pairwise comparisons were greater than the threshold of 0.10, the responses were reviewed immediately with the expert to allow him/her to recalibrate inconsistent judgments. This

careful control process ensured only logical expert evaluations (with high consistency scores "CR"<0.10) were aggregated to the global priority weights.

4.3. Data analysis

Step 1: Distribution channel evaluation hierarchical determination

The AHP requires establishing a hierarchical framework for the specific problem. This framework starts with the main objective at the top and decomposes into decision factors at progressively lower levels, ultimately resembling a network tree structure. Moving forward, we compared elements within each level of the hierarchy to those in the level above. At this stage, we identified four key distribution channel criteria: Temperature Control (TC), Transport Efficiency (TE), Storage Facility (SF), and Cost Optimization (CO). These criteria are detailed in Table 1 and represent the most relevant factors for achieving the overall objective. Finally, we defined a set of alternatives, each corresponding to the pre-defined options: TC1 - Technology integration, TC2 - Monitoring, TC3 - Packing integrity, TE4 - Efficient route planning, TE5 - Vehicle conditions, TE6 - Collaboration and information sharing, SF7 - Consistent and accurate temperatures, SF8 - Inventory rotation, SF9 – Block-chain integration, CO10 - Optimal delivery route, CO11- Warehouse management, CO12- Fleet management software. Finally, the hierarchy structure for choosing distribution channels for frozen food is shown in Fig. 2.

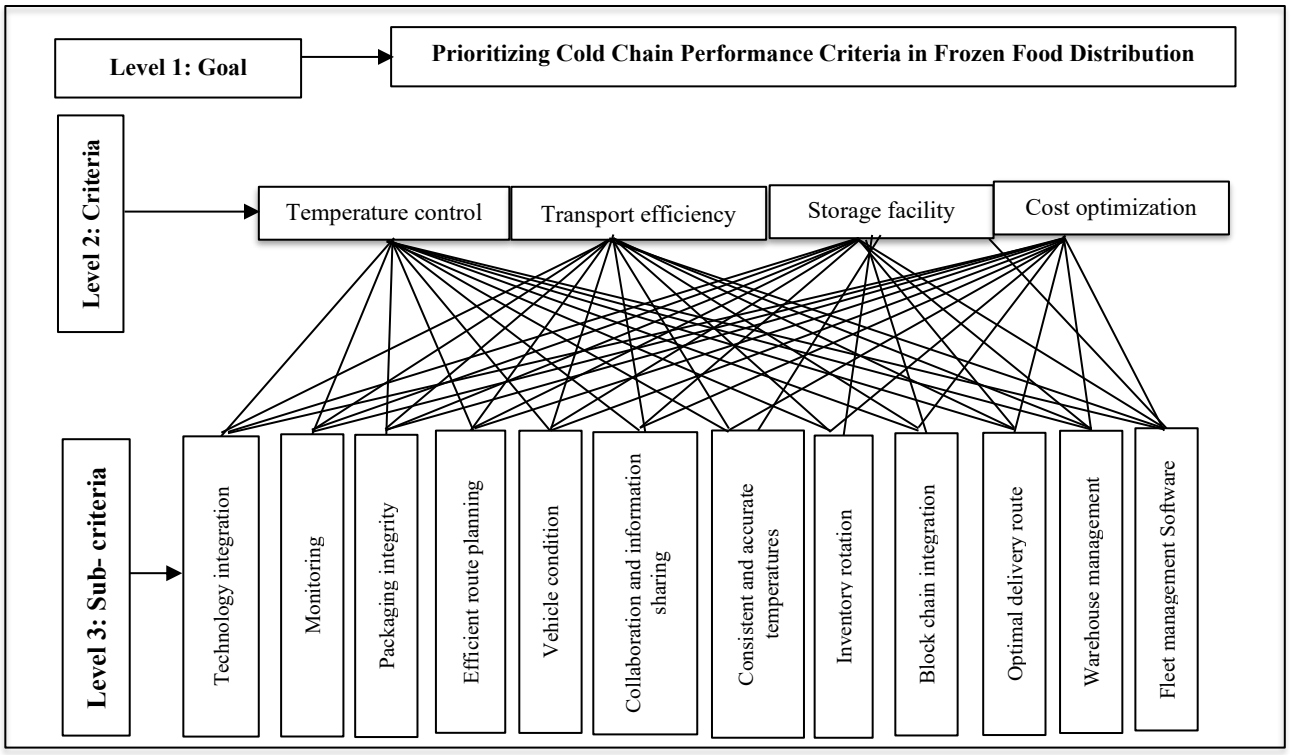


Fig. 2 Hierarchy structure of cold chain frozen food distribution

Step 2: Creating a relative importance matrix

After defining the structural elements, pairwise comparisons are conducted within the hierarchy. Saaty's scale of relative importance is employed to assess the relative significance of these elements in determining the distribution factor. In order to understand the pairwise comparisons of the AHP process, this study used a measurement scale developed by [11]. Usually, comparisons assign a higher rank (A) to a more important element (B). However, to assess the significance of developing scaling methods for hierarchical structures, a more nuanced approach is needed. This proposed numerical scale (0-9) bridges the gap by converting qualitative judgments (importance) into quantitative data. Here, 1 signifies equal importance (1:1), while 9 represents situations of critical importance as presented in Table 3.

Table 3. Measurement scale of the distribution channel factor

Importance	Explanation
1	Equally important
3	Weak importance
5	Strong importance
7	Demonstrated importance
9	Absolute importance
2,4,8	Intermediate values

The AHP relies on pairwise comparisons to assess different factors. For example, if comparisons between factors A and B are weighted three times more important than comparisons from B to A, this reflects a stronger emphasis on A's influence. This weighting ensures consistency throughout the analysis. Consequently, the comparison of B to A is automatically assigned a weight of one-third (1/3), reflecting the reciprocal relationship between the comparisons.

The mathematical representation of this form is;

$$A=\begin{pmatrix} 1 & A_{12} & \cdots & A_{1n} \\ A_{21} & 1 & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ A_{n1} & A_{n2} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & A_{12} & \cdots & A_{1n} \\ 1/A_{12} & 1 & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ 1/A_{1n} & 1/A_{2n} & \cdots & 1 \end{pmatrix}$$

$$= \begin{pmatrix} W_1/W_1 & W_1/W_2 & \cdots & W_1/W_n \\ W_2/W_1 & W_2/W_2 & \cdots & W_2/W_n \\ \vdots & \vdots & \cdots & \vdots \\ W_n/W_1 & W_n/W_2 & \cdots & W_n/W_n \end{pmatrix}$$

Where the weight of element i is represented by Wi; i; *i =1, 2, 3, . . ., n.*
a_{ij} refer to the ratio between two elements; *i, j = 1, 2, 3, . . ., n.*

Step 3: Determining the highest eigenvalue and eigenvector

After constructing a pairwise comparison matrix, researchers can determine the relative importance (weights) of the key elements at each hierarchical level. A common method for this is the eigenvalue

method, a well-established technique in numerical analysis for finding eigenvectors. These eigenvectors are then normalized based on specific criteria; (i) calculate the geometric mean for each row in the matrix; (ii) sum the linear means of the row vectors; (iii) determine the weight, Wi (Eigen vector), for each element based on specific criteria; (iv) calculate the average value using the weights (wi) and the corresponding values from the square matrix A (dimension *n x n*),; (v) calculate eigenvalue λmax. Eigenvector Wi (where m is the number of decision factors)

$$Wi = \left(\prod_{j=1}^{m} aij\right)1/_m \ / \sum_{i=1}^{m}\left(\prod_{j=1}^{m} aij\right)1/_m$$

Highest eigenvalue

$$\lambda_{max}\begin{pmatrix} 1 & a_{12} & . & . & . & a_{1m} \\ a_{21} & 1 & . & . & . & a_{2m} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a_{m1} & a_{m2} & . & . & . & 1 \end{pmatrix} X \begin{pmatrix} W_1 \\ W_2 \\ . \\ . \\ . \\ Wm \end{pmatrix} = \begin{pmatrix} W'_1 \\ W'_2 \\ . \\ . \\ . \\ W'_m \end{pmatrix}$$

Step 4: Consistency testing and iterative refinement

The output of AHP is directly related to the logical consistency of expert pairwise judgments. Subjectivity in human judgments in multi-attribute decision making can lead to inconsistency. To verify judgment validity, the Consistency Index (C.I.) is calculated using the maximum eigenvalue (λmax) and the matrix dimension (n):

$$C.I = \frac{\lambda_{max-n}}{n-1}$$

Next, the Consistency Ratio (C.R.) is calculated by comparing the C.I. with the standard Random Index (R.I.) for the matrix size (Saaty, 1980) as shown in Table 4:

$$C.R = \frac{\text{C.I}}{\text{R.I}}$$

An acceptable consistency threshold is defined as "C.R."<0.10. A 'C.R.'≥0.10 in the pairwise matrix indicates that the judgments are overly inconsistent. In these cases, an iterative feedback loop is activated, where the inconsistent comparison matrices are sent back to the expert for re-evaluation and re-calibration until the consistency threshold (C.R. <0.10) is reached. Matrices that satisfy this criterion are only synthesized into the overall priority weights.

Table 4 Values of the random index RI

n	1	2	3	4	5	6	7	8	9	10	11	12	13
R. I.	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.48	1.49	1.51	1.56

Source(s): Saaty (1980)

5. Results

5.1. Primary criteria prioritization

The empirical analysis of Malaysia's frozen food distribution network involving N = 20 senior industry experts result in a hierarchy of decisions which questions the cost-centric approach to logistics. The primary criteria pairwise comparison matrix obtained an overall Consistency Ratio (CR) of 0.035 (CI = 0.031 and λmax = 4.09) that falls within Saaty's threshold of 0.1, and further demonstrates inter-expert agreement across logistics directors, warehouse executives, and supply chain analysts as detailed in Table 5.

Table 5 Pairwise comparison matrix and priority weights for main criteria

Main criteria	Temperature control (TC)	Transport efficiency (TE)	Storage facility (SF)	Cost optimization (CO)	Weight	Rank	CI	CR
Temperature control (TC)	1.00	5.00	4.00	7.00	0.60	1	0.031	0.035
Transport efficiency (TE)	0.20	1.00	0.50	3.00	0.14	3		
Storage facility (SF)	0.25	2.00	1.00	3.00	0.20	2		
Cost optimization (CO)	0.14	0.33	0.33	1.00	0.06	4		

Note: $\lambda_{\max} = 4.09$, Consistency Index (CI) = 0.031, Consistency Ratio (CR) = 0.035

At the main criteria level, the empirical hierarchy distribution shows that Temperature Control (TC) has an overwhelming weight of 60% of the total decision weight (weight = 0.60, rank 1). The secondary

weight of Storage Facility (SF) is 0.20 (rank 2), and Transport Efficiency (TE) is 0.14 (rank 3). Cost Optimization (CO) has a low priority (6%) with a rank of 4. This asymmetry illustrates that temperature integrity is an absolute condition for operation of the system in tropical developing markets. Extreme outside temperature and humidity could cause high rates of temperature degradation during cross-docking and intermodal transfers. As a result, supply chain players value risk avoidance catastrophic risk avoidance, more than short term operational cost reduction.

5.2. Sub-criteria cluster local dynamics and mathematical integrity

The synthesis of local priority vectors for each criterion cluster reveals the particular operational mechanisms that affect the performance in each criterion. All four sub-criteria clusters met mathematical consistency criteria (TC, CR = 0.079; TE, CR = 0.025; SF, CR = 0.066; CO, CR = 0.091) in Table 6, validating the internal trade-off logic.

Table 6 Local priority weights and consistency ratios for sub-criteria clusters

Main criteria	Sub-criteria	Local weight	Local rank	C.R
TC	TC1	0.73	1	
	TC2	0.16	8	0.079
	TC3	0.11	10	
TE	TE4	0.72	2	
	TE5	0.19	7	0.025
	TE6	0.09	11	
SF	SF7	0.05	12	0.066
	SF8	0.61	3	
	SF9	0.34	5	
CO	CO10	0.58	4	
	CO11	0.31	6	0.091
	CO12	0.12	9	

Note: *All cluster Consistency Ratios (CR) remain strictly below the 0.10 threshold*

In the Temperature Control, Technology Integration (TC1) dimension, with a score of 0.73, it balances the score for Real-Time Monitoring (TC2 = 0.16) and Packaging Integrity (TC3 = 0.11); this means that the systemic digital architecture takes precedence to prevent the occurrence of temperature breaches, instead of just recording them and relying on passive insulation. The findings indicate that Efficient Route Planning (TE4 = 0.72) significantly surpasses Vehicle Conditions (TE5 = 0.19) and Information Sharing (TE6 = 0.09), thus making dynamic route optimization the biggest measure to defend against tropical

urban traffic delays that cause rapid product degradation. Storage Facilities results show that Inventory Rotation Techniques (SF8 = 0.61) are more relevant than Blockchain Integration (SF9 = 0.34) and Temperature Consistency (SF7 = 0.05), and floor-level rotation (FIFO/FEFO) is identified as a risk mitigation tool that can be implemented immediately to prevent local degradation in the microclimate. Finally, under Cost Optimization, Optimal Delivery Route Costing (CO10 = 0.58) is more important than Warehouse Management (CO11 = 0.31) and Fleet Management Software (CO12 = 0.12), focusing on cost-control measures where variable transit costs and total spoilage risks are greatest.

5.3. Global priority synthesis and theoretical alignment

Technology Integration (TC1) leads the global hierarchy, accounting for almost half of the total global decision weight (Global weight = 0.44, rank 1, see Table 7 and Fig. 3). Physical resources like refrigerated fleets or high-bay cold rooms are basic commodities of operation from the Resource-Based View (RBV) perspective. Instead, the sustainable competitive advantage is achieved with high-order digital capabilities, such as IoT sensor networks, automated telemetry and predictive temperature analytics, which could be substituted for protection against tropical ambient heat.

Table 7 Global weights and synthesis priority ranking of operational sub-criteria

Main criteria	Main criteria weight	Sub-criteria	Local priority weight	Global priority weight	Global rank
Temperature control (TC)	0.60	TC1-Technology integration	0.73	0.44	1
		TC2- Monitoring	0.16	0.10	4
		TC3-Packaging integrity	0.11	0.07	7
Transport Efficiency (TE)	0.14	TE4-Efficient route planning	0.72	0.13	2
		TE5-Vehicle conditions	0.19	0.04	9
		TE6- Collaboration and information sharing	0.09	0.06	8
Storage Facility (SF)	0.20	SF7- Consistent and accurate temperatures	0.05	0.09	5
		SF8- Inventory rotation techniques	0.61	0.12	3
		SF9-Block chain integration	0.33	0.08	6
Cost Optimization (CO)	0.06	CO10- Optimal delivery route	0.58	0.03	10
		CO-11Inventory management	0.31	0.02	11
		CO-12 Fleet management Software	0.12	0.01	12

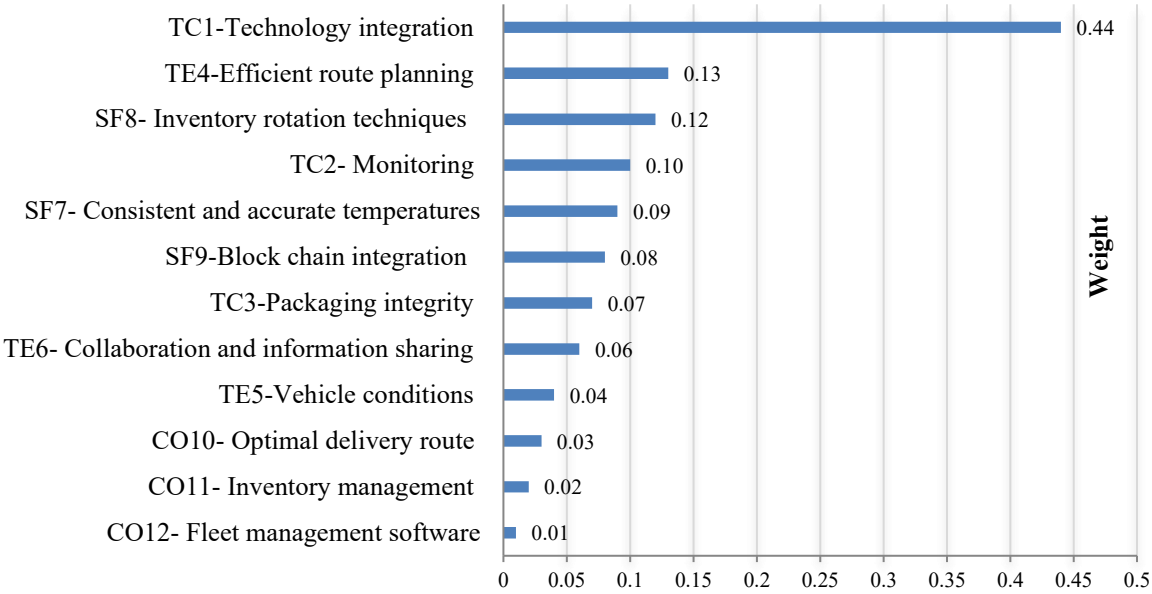


Fig. 3 Overall weight of the cold chain frozen food distribution

Under the Supply Chain Risk Management (SCRM) theory, the main operational drivers are those that act as an active protecting mechanism: Efficient Route Planning (TE4= 0.13, rank 2), Inventory Rotation Techniques (SF8 = 0.12, rank 3), and Real-Time Monitoring (TC2= 0.10, rank 4). Dynamic rerouting avoids unpredictable urban traffic jams, automated rotation (FIFO/FEFO) ensures no product ageing and degraded storage temperatures due to local microclimatic effects, and continuous telemetry gives early warning of thermal spikes during dock handling. Medium operational priorities include Consistent Temperatures (SF7 = 0.09), Blockchain Integration (SF9 = 0.08), Packaging Integrity (TC3 = 0.07), Collaboration and Information Sharing (TE6 = 0.06) and Vehicle Conditions (TE5 = 0.04). In contrast, all direct cost-optimization sub-criteria are filled under the global hierarchy: Optimal Delivery Route Costing (CO10 = 0.03, rank 10), Warehouse Management Costing (CO11 = 0.02, rank 11) and Fleet Management Software Costing (CO12 = 0.01, rank 12). This positioning is clear and indicates that cost optimization is not a primary decision-making driver, but is rather a secondary boundary. Operational savings in the short term create an undue risk of product spoilage, regulatory fines and brand damage. Thus, financial

optimization for the cold chains in the tropics is tightly bound to the non-negotiable food safety and temperature compliance conditions.

6. Discussion

This study's empirical results established a fundamental operating guideline for the distribution of frozen foods in the tropical developing market: Temperature integrity and proactive risk mitigation are absolute priorities over short-term minimization of financial costs. This study is an attempt to go beyond the isolated optimization model (such as static vehicle routing algorithms or warehouse layouts at the local level), but rather synthesize expert opinions from supply chain executives, logistics directors, and industry analysts and then validate them with the Analytic Hierarchy Process (AHP) to create an integrated decision hierarchy. The dominant weight of Temperature Control (TC = 0.60) over Cost Optimization (CO = 0.06) shows that cold chain operators in the tropics operate with a "safety first" approach, and that temperature compliance is considered a fundamental precondition.

6.1. Theoretical contributions to the Resource-Based View (RBV

This study builds on the Resource-Based View (RBV) in cold chain logistics by reinterpreting the dimensions of the Valuable Rare Inimitable Non-Substitutable (VRIN) capability in a high-risk environment. In logistics, traditional RBV applications often consider physical capital assets to be the primary source of sustained competitive advantage, such as a fleet of multi-temperature reefer vehicles or an automated high bay storage facility. The empirical hierarchy, however, shows that physical Storage Facilities (SF = 0.20) and Transport Efficiency (TE = 0.14) are only secondary and structural enablers. In tropical markets such as Malaysia, where the ambient heat and humidity are significant factors in promoting microbial growth during loading and cross-docking [6, 17], physical hardware is a standardized "table stakes" commodity, not a competitive insulation commodity [12]. Rather, the overwhelming global priority captured by Technology Integration (TC1 = 0.44, global rank 1) shows empirically that competitive differentiation does not come from lower-order digital capabilities. Operational excellence happens when cold chain service providers do not merely invest in more physical

fleet capacity, but also when they add more intelligence to those physical assets in the form of IoT-equipped real-time telemetry, automated climate sensors, and predictive temperature analytics [18, 62]. The digital capabilities result in complex dynamic routines which are causally ambiguous, socially complex and hard to imitate, thus giving life to the RBV principles in the tropical supply chain networks [13, 15].

6.2. Theoretical contributions to Supply Chain Risk Management (SCRM)

The empirical findings provide important theoretical nuances to the literature on Supply Chain Risk Management (SCRM) in terms of redefining the role of cost optimization in the context of risk-averse Supply Networks [14]. In traditional operations research models, the main objective function is often the minimization of financial cost, and product quality and temperature safety are treated as secondary constraints [63]. The bottom-level global positioning of all direct financial sub-criteria Optimal Delivery Route Costing (CO10 = 0.03, rank 10), Warehouse Management Costing (CO11 = 0.02, rank 11), and Fleet Management Software Costing (CO12 = 0.01, rank 12) empirically reverses this assumption. Cost optimization is a clear case of a secondary boundary condition that is secondary to strict food safety requirements in tropical cold chains [7]. Furthermore, the global priorities of core operational drivers indicate an active risk mitigation approach: Efficient Route Planning (TE4 = 0.13, rank 2), Inventory Rotation Techniques (SF8 = 0.12, rank 3) and Real-Time Monitoring (TC2 = 0.10, rank 4). This results in a rational decision by operators to accept higher variable operational costs (e.g., dynamic rerouting algorithms, continuous telemetry) to minimize the risk of catastrophic losses, as temperature abuse is caused by static delays due to tropical urban congestion [8, 30]. Although the financial losses incurred from a single temperature breach are much greater than the short-term savings in costs of operation [14, 19, 25], both to product recalls and regulatory penalties under national standards, as well as permanent brand destruction.

7. Implications of the study

The empirical priorities established by this multi-criteria decision model translate directly into strategic, operational, and regulatory action items for supply chain stakeholders in tropical emerging markets. By anchoring resource allocation decisions to the empirical global weights, organizations and regulatory bodies could move away from ad-hoc capital deployment and align investments with validated operational directions.

7.1. Practical and managerial implications

(i) **Strategic capital reallocation:** Capital expenditure (CapEx) has traditionally been focused on logistics executives and supply chain directors on expansion of static warehouse space or expanding their fleet of physical transport. The absolute dominance shows that the combination of physical capacity and a lack of digital visibility is decreasing in tropical environments (TC1 = 0.44, global rank 1).

***Action plan*:** Supply chain leaders are to reprioritize the CapEx from pure vehicle acquisition to modifying current physical assets with networks of multi-sensors and telemetry, automatic temperature logging, and predictive thermal modelling.

Operational mechanism: Real-time temperature monitoring (TC2 = 0.10, global rank 4) can enable managers to switch from passive to active and responsive cold chains that can identify when cargo is starting to spoil due to ambient heat spikes during dock handling.

(ii) **High-leverage operational interventions:** Efficient Route Planning (TE4 = 0.13, global rank 2) and Inventory Rotation Techniques (SF8 = 0.12, global rank 3) are the two areas of operation where intervention will have the most impact on risk mitigation.

Fleet and transport operations: Logistics managers need to use dynamic, traffic sensor route optimization software which incorporates real-time traffic information, weather and ambient temperature forecasts. Directly reduce exposure of vehicles to ambient heat and minimize the

time of engine idling in tropical urban areas by re-routing to avoid unexpected traffic congestion.

Cold storage operations: Warehouse managers need to implement automated solutions for managing stock, such as Automated Storage and Retrieval Systems (AS/RS) that follow the First-In, First-Out (FIFO) principle and have been programmed to follow First-Expired, First-Out (FEFO). Automated rotation reduces dwell times, as well as eliminating microclimate product aging within high bay cold storage units.

(iii) Framing cost optimization constrained Boundary

These subordinate global rankings of direct cost sub-criteria (CO10 = 0.03, CO11 = 0.02, CO12 = 0.01) give clear guidance to corporate leadership.

Management mindset: Key performance Indicators (KPIs) for cold chain managers would not include short-term cost savings (e.g. turning off active refrigeration units when empty backhauls or delaying reefer fleet maintenance) at the expense of meeting temperature requirements.

Cost optimization: Cost optimization act as a secondary operational boundary, not a primary driver. When prioritized over thermal compliance, the operational savings achieved are easily wiped out by the far greater costs of product recalls, regulatory fines, and brand damage resulting from a single thermal failure.

7.2. Policy, food safety, and governance implications

Public policy and food governance systems play a crucial role in creating legal and binding requirements to reduce post-harvest food loss and ensure food safety. In the tropical developing markets, current cold chain regulations are usually based on point of destination checks (PoD) and do not adequately report actual thermal excursions between intermodal transfers and at loading docks. The empirical priorities derived in this study will give national standards bodies (e.g. those enforcing MS 2400-1) and agricultural

policy makers an empirical model to guide them from reactive checking to proactive digital monitoring. Regulatory bodies can say goodbye to unmonitored "dark spots" in the distribution network with the emphasis placed on real-time continuous telemetry and dynamic inventory rotation. Moreover, these insights around the world could be used to create targeted subsidy and grant programs by governments. Public incentives should be limited to digital telemetry, automated storage systems (AS/RS) and regional cold storage hubs, instead of providing generic capital subsidies for vehicle fleets. These policy interventions directly reduce the rate of thermal spoilage, mitigate transit bottlenecks, and enhance overall national food security in tropical developing economies. Table 8 synthesizes the key regulatory mechanism, and depicts the individual and specific AHP performance drivers directly linked to the macro-level policy goals and expected food safety ecosystem impacts.

Table 8. Policy and regulatory framework mapped to AHP empirical drivers

Policy objective	**Regulatory mechanism**	**Targeted AHP driver**	**Impact on cold chain ecosystem**
Mandatory temperature visibility	Standardized IoT telemetry regulations	**TC1 / TC2** (Weight: 0.54)	Eliminates unmonitored "dark spots" during intermodal transfers and loading docks
National infrastructure mandate	Cold chain modernization grants and subsidies	**TE4 / SF8** (Weight: 0.25)	Accelerates private adoption of AS/RS warehousing and dynamic routing technologies.
Cross-nodal standardization	Enforced compliance via MS 2400-1 audits	TC3 / TE6 (Weight: 0.13)	Standardizes temperature protocols across producers, 3PLs, and retail hypermarkets.

Building upon the structural mapping in Table 7, regulatory authorities could focus implementation efforts across two Strategic priorities:

(i) **Modernizing national cold chain regulations:** National standards agencies and government regulatory bodies (e.g. MS 2400-1 Malaysian Standard Cold Chain Logistics Operations) would plan new national compliance frameworks.

Regulatory action: Regulatory requirements could move from point-of-destination static checks to continuous temperature logging throughout the entire transit process, and have it digitally verified.

Enforcement: Requirements for continuous temperature monitoring through IoT as a condition for the operating license of the cold chain provide complete cross-nodal traceability and make logistics service providers responsible for temperature fluctuations that take place at intermodal transfer points.

(ii) **Targeting public incentive frameworks and subsidies:** Governments could create specific tax and capital grant programs tailored directly to empirical drivers that have priority in order to encourage faster expansion of cold chain infrastructure in emerging markets.

Specific incentives: Instead of giving general capital subsidies, it is better for the government to have some incentives that will be targeted to digital investments (IoT sensor networks, blockchain traceability platforms, and dynamic routing software).

Public infrastructure support: Public expenditure is needed on regional hubs for the cold chain, on automated loading docks and on dedicated freight corridors to help alleviate congestion in the urban transport system, directly contributing to the high-priority aim of reducing transit time under the ambient tropical heat.

8. Limitations and future research

Although this study is theoretically and empirically making several contributions, it has three major limitations that need to be highlighted:

(i) **Geographical scope:** The empirical data collection only took place in the frozen food distribution system within Malaysia. Malaysia is a representative model for the tropical developing economy but the exact numerical weights might not be applicable in non-tropical markets or in highly developed markets for cold chain.

(ii) **Methodological linear assumptions**: The basic AHP methodology is linear and unidirectional, i.e., it follows the hierarchy from criteria to sub-criteria. As a result, possible inter-criteria feedback loops, dependencies, and/or contextual trade-offs between criteria (e.g., the direct link of dynamic route planning to fuel cost metrics) were not explicitly modeled in this linear hierarchy.

(iii) **Sectoral granularity:** Expert panel considered the frozen food sector's cold chain ecosystem in its entirety. The model does not account for the different sub-categories of products (e.g., highly perishable raw seafood, poultry, ice cream, frozen plant-based protein) which may have different thermal tolerance limits and operational risk.

Based on these empirical findings and the identified limitations, future studies could delve into the following ways:

(i) **Cross-national comparative studies:** Replication and validation of this MCDM framework in other comparative emerging markets (e.g., Indonesia, Vietnam, Thailand) in Southeast Asia and other tropical developing regions are encouraged to measure priority stability and institutional boundary conditions.

(ii) **Methodological extensions (Fuzzy-AHP and ANP):** Future studies should use hybrid decision-making methods such as Fuzzy-AHP and Analytic Network Process (ANP). The advantages of fuzzy frameworks are that they can represent ambiguity and vagueness of experts' judgements, and ANP can represent complex inter-dependencies, feedback loops and dynamic interaction effects between cold chain criteria.

(iii) **Category-specific and AI-driven modeling:** Targeted empirical evaluation of specific categories of high-value and high-risk frozen products, including seafood or vaccines, should be carried out by researchers. Furthermore, research can focus on incorporating these empirical AHP weights into predictive cooling models, machine learning-based vehicle routing systems and artificial intelligence-based disruption management systems for dock scheduling in the event of climate disturbances of transport.

9. Conclusion

The Analytic Hierarchy Process (AHP) is employed in this study to develop an empirical multi-criteria decision-making framework to evaluate and prioritize the performance criteria for frozen food distribution in tropical emerging markets. The empirical results reveal that there is an asymmetric priority hierarchy, with Temperature Control (TC = 0.60) dominating the decision space, Storage Facility (SF = 0.20), Transport Efficiency (TE = 0.14) and Cost Optimization (CO = 0.06). The sub-criteria scores at the global level are as follows: Technology Integration (TC1 = 0.44) with nearly half of the total global score, Efficient Route Planning (TE4 = 0.13), Inventory Rotation Techniques (SF8 = 0.12) and Real-Time Monitoring (TC2 = 0.10). On the other hand, direct cost-optimization drivers are in the back end of the global priority list. The results validate the fact that tropical cold chain operators are operating from a safety-first approach, meaning that temperature compliance and food safety preservation are of absolute priority and not a short-term direct cost reduction strategy. This study make a specific three contribution for scholar and practitioner in the following ways: (i) Theoretical Advancement: It illustrates that sustainable competitive advantage in tropical cold chains is built on high-order digital capabilities known as RBV (Resource Based View of the firm) and not simply generic physical infrastructure; cost optimization is a secondary boundary condition constrained by non-negotiable food safety parameters known as SCRM (Supply Chain Risk Management); (ii) Methodological Baseline: It offers a methodologically ground based decision hierarchy, specifically calibrated to the climatic, structural and regulatory realities of developing cold chain networks in the tropics; (iii) Practical and Policy Guidance:

It provides supply chain executives and policymakers with an empirical roadmap to target capital deployment towards IoT-enabled real time telemetry systems, automated warehousing systems (AS/RS), dynamic route optimization, and modernized national cold chain regulatory enforcement.

References

1. Sen S, Antara N, Sen S. Factors influencing consumers' to Take Ready-made Frozen Food. Curr Psychol. 2021;40(6):2634–43.
2. Malaysian Investment Development Authority. Kawan Food to ride on growing frozen food demand [Internet]. MIDA. 2021. Available from: https://www.thestar.com.my/business/business-news/2021/01/15/kawan-to-ride-on-growing-frozen-food-demand
3. ReportLinker. Frozen Food Market Overview in Malaysia 2023-2027 [Internet]. 2023. Available from: https://www.reportlinker.com/market-report/Frozen-Food/5387/Frozen-Food?term=frozen food industry&matchtype=b&loc_interest=&loc_physical=9066575&utm_group=standard&utm_term=frozen food industry&utm_campaign=ppc&utm_source=google_ads&utm_medium=paid_ads&ut
4. Malaysian International Food & Baverage. Frozen Food [Internet]. 2023. Available from: https://mifb.com.my/frozen-food/#:~:text=The Frozen Food market in,15.2 billion respectively by 2027.
5. BizVibe. Frozen Food Industry in Malaysia: Extensive Analysis [Internet]. BizVibe Blog. 2018. Available from: https://blog.bizvibe.com/blog/food-beverages/frozen-food-industry-malaysia
6. Skawińska E, Zalewski RI. Economic Impact of Temperature Control during Food Transportation—A COVID-19 Perspective. Foods. 2022;11(3).
7. Leng L, Wang Z, Zhao Y, Zuo Q. Formulation and heuristic method for urban cold-chain logistics systems with path flexibility – The case of China. Expert Syst Appl [Internet]. 2024;244(November 2023):122926. Available from: https://doi.org/10.1016/j.eswa.2023.122926

8. Pajić V, Andrejić M, Chatterjee P. Enhancing Cold Chain Logistics: A Framework for Advanced Temperature Monitoring in Transportation and Storage. Mechatronics Intell Transp Syst. 2024;3(1).
9. Zhou L, Li Q, Li F, Jin C. Research on Green Technology Path of Cold-Chain Distribution of Fresh Products Based on Sustainable Development Goals. Sustain. 2022;14(24).
10. Liverpool-tasie LSO, Wineman A, Emenekwe CC, Fang M, Olunuga O, Onyeneke RU, et al. Rapid transformation in aquatic food value chains in three Nigerian states. Front Aquac. 2024;3(1302100):1–14.
11. Saaty TL. The analytic hierarchy process. McGraw-Hill; 1980.
12. Cui L, Gao M, Dai J, Mou J. Improving supply chain collaboration through operational excellence approaches: an IoT perspective. Ind Manag Data Syst. 2022;122(3):565–91.
13. Barney JB. Purchasing, Supply Chain Management and Sustained Competitive Advantage: The Relevance of Resource-based Theory. J Supply Chain Manag. 2012;3–6.
14. Fan Y, Stevenson M. A review of supply chain risk management: definition, theory, and research agenda. Int J Phys Distrib Logist Manag. 2018;48(3):205–30.
15. Góral-Kowalczyk M, Góral D, Nakonieczny P. Analysis of Transport Conditions for Frozen Food on the Way from the Shop to Home. Transp Telecommun. 2023;24(2):97–109.
16. Zhang L, Fu M, Fei T, Lim MK, Tseng M-L. A cold chain logistics distribution optimization model : Beijing-Tianjin-Hebei region low-carbon site selection. Ind Manag Data Syst. 2023;
17. Maiyar LM, Ramanathan R, Roy I, Ramanathan U. A Decision Support Model for Cost-Effective Choice of Temperature-Controlled Transport of Fresh Food. Sustain. 2023;15(8).
18. Ramanathan U, Ramanathan R, Adefisan A, Da Costa T, Cama-Moncunill X, Samriya G. Adapting Digital Technologies to Reduce Food Waste and Improve Operational Efficiency of a Frozen Food Company—The Case of Yumchop Foods in the UK. Sustain. 2022;14(24).
19. Vu N, Ghadge A, Bourlakis M. Blockchain adoption in food supply chains: a review and

779 implementation framework. Prod Plan Control [Internet]. 2023;34(6):506–23. Available from:
780 https://doi.org/10.1080/09537287.2021.1939902
781 20. Cai C, Mo J, Lu Y, Zhang N, Wu Z, Wang S, et al. Integration of a porous wood-based
782 triboelectric nanogenerator and gas sensor for real-time wireless food-quality assessment. Nano
783 Energy [Internet]. 2021;83(February):105833. Available from:
784 https://doi.org/10.1016/j.nanoen.2021.105833
785 21. Kafi MA, Melan M, Adam B, Kah Loon C, Zainuddin N, Abualrejal H. Digitalization of freight
786 transport and logistics industry in Malaysia. In: International Conference on Intelligent
787 Technology, System and Service for Internet of Everything (ITSS-IoE). IEEE; 2022.
788 22. Moureh J, Laguerre O, Flick D, Commere B. Analysis of use of insulating pallet covers for
789 shipping heat-sensitive foodstuffs in ambient conditions. Comput Electron Agric. 2002;34(1–
790 3):89–109.
791 23. Fauziana DR, Marimin, Suwarsinah HK, Prasetio EA. What factors impact the adoption of
792 postharvest loss-reduction technologies in mangosteen supply chain? J Open Innov Technol Mark
793 Complex [Internet]. 2023;9(3):100102. Available from:
794 https://doi.org/10.1016/j.joitmc.2023.100102
795 24. Estrada-Flores S, Eddy A. Thermal performance indicators for refrigerated road vehicles. Int J
796 Refrig. 2006;29(6):889–98.
797 25. Malaysian Standard. Halal supply chain management system – Part 1: Transportation – General
798 requirements (First revision). 2019.
799 26. ReportLinker. Malaysia Frozen Food Industry Outlook 2022 - 2026. 2022.
800 27. Chang MS, Chen S, Hsueh CF. Real-time vehicle routing problem with time windows and
801 simultaneous delivery/pickup demands. J East Asia Soc Transp Stud [Internet]. 2003;5(30):2273–
802 2286. Available from: http://www.easts.info/2003journal/papers/2273.pdf
803 28. Prapinit P, Kafi A, Osman NHB, Melan M. Navigating COVID-19 Challenges in Malaysian

Haulage Industry. Int J Sustain Dev Plan. 2024;19(3):1033–9.

29. Zhang Y, Chen XD. An optimization model for the vehicle routing problem in multiproduct frozen food delivery. J Appl Res Technol [Internet]. 2014;12(2):239–50. Available from: http://dx.doi.org/10.1016/S1665-6423(14)72340-5

30. Pillac V, Gendreau M, Guéret C, Medaglia AL. A review of dynamic vehicle routing problems. Eur J Oper Res [Internet]. 2013;225(1):1–11. Available from: http://dx.doi.org/10.1016/j.ejor.2012.08.015

31. Hsu CI, Chen WT, Wu WJ. Optimal delivery cycles for joint distribution of multi-temperature food. Food Control [Internet]. 2013;34(1):106–14. Available from: http://dx.doi.org/10.1016/j.foodcont.2013.04.003

32. Ouyang Y. The effect of information sharing on supply chain stability and the bullwhip effect. Eur J Oper Res. 2007;182(3):1107–21.

33. Teuteberg V, Kluth IK, Ploetz M, Krischek C. Effects of duration and temperature of frozen storage on the quality and food safety characteristics of pork after thawing and after storage under modified atmosphere. Meat Sci [Internet]. 2021;174:108419. Available from: https://doi.org/10.1016/j.meatsci.2020.108419

34. Rahman MS. Hnadbook of Food Preservation. Second. CRC Press Taylor & Francis Group. CRC Press Taylor & Francis Group; 2007.

35. Pham T. Refrigeration in Food Preservation and Processing [Internet]. Suvendu Bhattacharya, editor. Wiley & Son Ltd. In United States: John Wiley & Sons Inc; 2014. Available from: https://onlinelibrary.wiley.com/doi/epdf/10.1002/9781118406281.ch15

36. Matić D, Filipović V, Savić A, Stanimirović Z. A genetic algorithm for solving multiple warehouse layout problem. Kragujev J Math. 2011;35(1):119–38.

37. Fellows P. Food Processing Technology Principles and Practice. Third. A volume in Woodhead Publishing Series in Food Science, Technology and Nutrition. Woodhead Publishing Limited;

2009.

38. Pérez-Lechuga G, Martínez-Sánchez JF, Venegas-Martínez F, Madrid-Fernández KN. A Routing Model for the Distribution of Perishable Food in a Green Cold Chain. Mathematics. 2024;12(2):1–27.

39. Iftekhar A, Cui X. Blockchain-based traceability system that ensures food safety measures to protect consumer safety and COVID-19 free supply chains. Foods. 2021;10(6).

40. Prapinit P, Kafi A, Osman NH, Melan M. IoT in Courier Services: Impact on Customer Satisfaction and Supply Chain Sustainability. Int J Sustain Dev Plan. 2024;19(2):671–9.

41. Miao C, Liu H, Zhu GG, Chen H. Connectivity-based optimization of vehicle route and speed for improved fuel economy. Transp Res Part C Emerg Technol [Internet]. 2018;91:353–68. Available from: https://doi.org/10.1016/j.trc.2018.04.014

42. Alszer S, Krystek J. The Importance of Internal Transport in Organizing High-Bay Warehouses. Logist Transp [Internet]. 2017;35(3):37–44. Available from: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,sso&db=bth&AN=127754099&site=ehost-live&custid=s1020214

43. Zaerpour N, Volbeda R, Gharehgozli A. Automated or manual storage systems: Do throughput and storage capacity matter? Infor Inf Syst Oper Res [Internet]. 2019;57(1):99–120. Available from: https://doi.org/10.1080/03155986.2018.1532765

44. Stanković R, Rogić K, Šafran M. Saving Energy by Optimizing Warehouse Dock Door Allocation. Energies. 2022;15(16).

45. Li Y-CM, Chen Y-HA. Assessing the thermal performance of three cold energy storage materials with low eutectic temperature for food cold chain. Energy. 2016;15:238–56.

46. Macbeth D. Distribution: Planning and control [Internet]. Third. Vol. 15, European Management Journal. New York: springer; 2018. 102–103 p. Available from: file:///C:/Users/User/Downloads/978-1-4899-7578-2.pdf

47. Ndraha N, Hsiao HI, Vlajic J, Yang MF, Lin HTV. Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations. Food Control. 2018;89:12–21.
48. Kafi A, Zainuddin N, Saifudin AM, Shahron SA, Razalli MR, Musa S, et al. Meta-analysis of food supply chain: pre, during and post COVID-19 pandemic. Agric Food Secur [Internet]. 2023;12(1):1–22. Available from: https://doi.org/10.1186/s40066-023-00425-5
49. Ristanović V, Tošović-Stevanović A, Maican S, Muntean A. Economic overview of the distribution channels used by Eastern European small farms for their agricultural products. Agric Econ (Czech Republic). 2022;68(8):299–306.
50. Beiki H, Mohammad Seyedhosseini S, Ponkratov V V., Zekiy AO, Ivanov SA. Addressing a sustainable supplier selection and order allocation problem by an integrated approach: a case of automobile manufacturing. J Ind Prod Eng [Internet]. 2021;38(4):239–53. Available from: https://doi.org/10.1080/21681015.2021.1877202
51. Pereira V de F, Doria ECB, Carvalho B da C, Neves Filho L de C, Silveira V. Evaluation of temperatures in a refrigerated container for chilled and frozen food transport. Cienc e Tecnol Aliment. 2010;30(1):158–65.
52. Talbot L, Purnell G, James SJ, James C. Operating temperatures of supermarket frozen retail display cabinets. Int J Refrig [Internet]. 2020;117:81–93. Available from: https://doi.org/10.1016/j.ijrefrig.2020.04.017
53. Meneghetti A, Ceschia S. Energy-efficient frozen food transports: the Refrigerated Routing Problem. Int J Prod Res [Internet]. 2020;58(14):4164–81. Available from: https://doi.org/00207543.2019.1640407
54. Nha Trang NT, Nguyen TT, Pham H V., Anh Cao TT, Trinh Thi TH, Shahreki J. Impacts of Collaborative Partnership on the Performance of Cold Supply Chains of Agriculture and Foods: Literature Review. Sustain. 2022;14(11).
55. Heldman DR. Food Freezing and Frozen Food Storage. In: Dennis R. Heldman, Daryl B. Lund

CS, editor. Handbook of Food Engineering [Internet]. 3rd ed. CRC Press; 2019. p. 46. Available from: https://www.taylorfrancis.com/books/edit/10.1201/9780429449734/handbook-food-engineering-dennis-heldman-daryl-lund-cristina-sabliov?refId=5d2af4a8-7af8-48d1-80c7-e13c6bb48ac4&context=ubx

56. Turan C, Ozturkoglu Y. A conceptual framework model for an effective cold food chain management in sustainability environment. J Model Manag. 2022;17(4):1262–79.

57. Chavalala MM, Bag S, Pretorius JHC, Rahman MS. A multi-method study on the barriers of the blockchain technology application in the cold supply chains. J Enterp Inf Manag. 2022;37(2):745–76.

58. Xing E, Cai B. Delivery Route Optimization Based on Deep Reinforcement Learning. In: Proceedings - 2020 2nd International Conference on Machine Learning, Big Data and Business Intelligence, MLBDBI 2020. 2020. p. 334–8.

59. Yu W, Hou G, Xia P, Li J. Supply chain joint inventory management and cost optimization based on ant colony algorithm and fuzzy model. Teh Vjesn. 2019;26(6):1729–37.

60. Nakandala D, Lau H, Zhang J. Strategic hybrid lateral transshipment for cost-optimized inventory management. Ind Manag Data Syst. 2017;117(8):1632–49.

61. Lukman RK, Cerinšek M, Virtič P, Horvat B. Improving efficient resource usage and reducing carbon dioxide emissions by optimizing fleet management for winter services. J Clean Prod. 2018;177(May 2014):1–11.

62. Kafi MA, Melan M, Saifudin ABM, Loon CK, Zainuddin N Bin, Abualrejal H. Digitalization of freight transport and logistics industry in Malaysia. In: International Conference on Intelligent Technology, System and Service for Internet of Everything, ITSS-IoE 2022. IEEE; 2022.

63. Izadi R, Wagner D, Löpitz D, Zopp C, Klaerner M, Michel A, et al. Machine learning-enhanced modelling and experimental analysis of foam-core thermoplastic composites produced via pultrusion. Compos Part B [Internet]. 2026;314:113476. Available from:

https://doi.org/10.1016/j.compositesb.2026.113476