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Assessing risks in air cold chain logistics for time- and temperature-sensitive products: A case of Taiwan

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A R T I C L E I N F O

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A B S T R A C T

This study investigates critical hazards associated with air transportation within cold chain logistics, focusing on the delivery of time-sensitive and perishable goods. Despite the growing importance of maintaining strict temperature control, there is a notable gap in research specifically targeting hazards in air cold chain logistics. Through an extensive literature review, 15 key hazards were identified and systematically categorized into five major groups: shipper, aircraft, apron, warehouse, and customs. To quantitatively assess these hazards, a hybrid approach combining Failure Modes and Effects Analysis (FMEA) with a Rule-based Bayesian Network (RBN) was employed, complemented by sensitivity analysis to ensure model robustness. Results reveal that hazards related to the shipper, aircraft, and apron exert the greatest impact, highlighting the critical role these stakeholders play in maintaining cold chain integrity. Based on these findings, targeted recommendations are proposed to mitigate risks effectively. The insights gained aim to enhance operational performance and reliability in air cold chain logistics, thereby strengthening the competitiveness and sustainability of the air cargo industry. This research helps bridge the existing knowledge gap and offers a practical framework for risk management in air cold chain transportation.

1. Introduction

Driven by the global pandemic, deliveries of food and pharmaceuticals via cold chain logistics have gradually become a critical operational standard. Cold chain logistics is attracting increasing attention due to its vital role in ensuring food safety and the transportation of time- and temperature-sensitive products such as vaccines, pharmaceuticals and fresh food that are easily damaged and influence quality during transportation with an inaccurate temperature range (Huang et al., 2024). According to the International Trade Administration (2022), approximately $400 billion in pharmaceutical goods are transported globally each year, alongside a concurrent rise in demand for temperature-controlled transportation and storage in the healthcare logistics industry. The global cold chain logistics sector demonstrates consistent expansion. With a market value of USD 293.58 billion in 2023 and USD 324.85 billion in 2024, projections indicate a substantial increase to USD 862.33 billion by 2032, reflecting a significant growth trend. (Fortune Business Insights, 2024).

Unlike conventional logistics, cold chain logistics requires specialized facilities and meticulous planning to store temperature-sensitive goods in a controlled environment. In global cold chains, temperature-sensitive products are mainly transported by ocean and air freight. Although maritime transport is generally more cost-effective, air transport plays a vital role in ensuring the rapid and secure delivery of high-value goods that are both time- and temperature-sensitive (Magdalena, 2021). Choi (2023) highlighted the risks associated with transporting time-sensitive products, particularly the potential for damage or deterioration caused by temperature fluctuations during loading and unloading. Therefore, air transportation serves as the most critical mode for delivering temperature- and time-sensitive goods.

The International Air Transport Association (IATA, 2021) reported that approximately 20 % of time-sensitive products are damaged or discarded due to inadequate supply chain management. Although IATA emphasizes that product value and delivery urgency drive the choice of air transport, significant risk from improper operations or management persists, despite its critical role in cold chain logistics. Therefore, understanding the potential hazards throughout the transportation process is crucial for enhancing the reliability and efficiency of air cold chain

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logistics.

Additionally, as Taiwan's main international gateway, Taiwan Taoyuan International Airport is Asia's best-connected airport for cargo handling. It is ranked among the world's top ten airports in cargo volume and plays a crucial role in regional and international logistics. This prominence highlights Taoyuan Airport's strategic importance in air cargo transport, underscoring the representativeness and significance of using it as a case study for cold chain logistics research. Findings from this context can provide valuable insights and benchmarks applicable to other major airports in Asia and globally, thereby advancing cold chain risks understanding and management in air cargo operations.

The main contributions of this research include (1) identifying and assessing a list of hazards of cold chain operations in air cargo delivery, (2) proposing a list of recommendations and implications for the industry to deal with the hazards, (3) raising the attending of the importance of air cold chain logistics and (4) filling the research gap and providing suggestions for the relevant research. The rest of the paper is organized as follows: Section 2 reviews the literature on temperature-sensitive products in cold chain logistics and identifies the relevant hazards. Section 3 describes a hybrid method to assess the risk of aviation cold chain logistics. Section 4 presents the results and implications. The conclusion is drawn in Section 5.

2. Literature review

2.1. Cold chain logistics

Cold chain logistics, a specialized branch of supply chain management, involves transporting and handling temperature-controlled goods whose quality and economic value degrade rapidly over time. It covers refrigerated production, distribution, and storage processes that preserve product quality and safety (Accorsi et al., 2018; Ye et al., 2022; Zhang et al., 2020). Temperature deviations during transport or storage, sometimes exceeding the recommended range by more than 10 °C, can cause severe degradation. Even a minor 2 °C fluctuation during vaccine transport may render an entire shipment unusable, leading to significant financial losses and public health risks (Mizrak & Cantürk, 2025; Ye et al., 2022).

Pharmaceuticals, fresh food, and biotech products require fast delivery, temperature control, and minimal handling. While maritime transport offers high capacity at lower cost, it is slow, and road transport often lacks the timeliness required for sensitive cargo. Thus, air transport remains the preferred mode. According to IATA (2025a), air freight handles over 62 million tonnes of cargo yearly, less than 1 % of global trade by volume but over 33 % by value, or about $8.3 trillion, underscoring its strategic role in high-value and time-sensitive logistics. Boeing (2024) further projects a 4.0 % annual growth in air cargo traffic from 2024 to 2043, signaling sustained demand and the need for focused risk assessment.

Overall, to evaluate key risks in cold chain logistics, prior studies have employed the Best–Worst Method (Ding et al., 2023), genetic algorithms (Kulak et al., 2018), and FMEA for food safety assessment (Aleksic et al., 2022; Wu & Hsiao, 2021). While these studies focused on general cold chain or food safety risks, the present study applies FMEA specifically to air cold chain logistics, offering a systematic assessment of temperature-sensitive cargo and operational vulnerabilities unique to aviation.

2.2. Hazards of air cold chain logistics

IATA (2020) identified three key shortcomings impacting the air cargo market, including (1) non-compliance, and lack of standardization, accountability, and transparency in the air transport supply chain, which lead to numerous temperature excursions occurring under the responsibility of airlines and airports; (2) temperature deviations that compromise product quality, rendering them ineffective or unsafe, thus diminishing their value and potentially harming end-users; and (3) operational failures resulting in products being lost, discarded, or returned, incurring substantial costs for stakeholders. Aprons could be a significant and vulnerable area for temperature excursion, especially when goods are staged before or during loading and unloading (Chaomuang et al., 2024; Medicines & Healthcare Products Regulatory Agency, 2019). Thus, advancement in packaging technology and ground handling equipment significantly improves the transportation stability of time-sensitive cargoes (Choi, 2023). However, Chaomuang et al. (2024) observed that most ground operations, including customs procedures and storage in cargo cold rooms, are conducted at ambient temperatures. This practice leads to variations in both ambient and product temperatures, potentially compromising product integrity (Mercier et al., 2017). Several studies have demonstrated that temperature fluctuations during loading, in-flight, and unloading phases can deviate from the suggested temperatures to store goods, affecting the quality of temperature-sensitive products (Mai et al., 2012).

Many hazards might arise during the actual operation process, including issues related to personnel, equipment and information communications (Liu & Li, 2021). Zheng et al. (2020) categorized cold chain logistics systems hazards into four types, with "transportation and distribution" ranked as the most important one, followed by "processing and packaging", "information processing", and "warehousing". A single failure to maintain the correct temperature during delivery would cause product spoilage, product losses, and ultimately, financial losses. Therefore, a thorough understanding of air transportation processes is essential for accurately evaluating risk and its impacts on cold chain logistics. The process of air cold chain logistics service extends from shippers to destinations. Activities of air cold chain logistics are shown in Fig. 1, which helps evaluate the risks and their effects on air cold chain logistics. This study explores potential risk factors in air cold chain logistics that prone to temperature deviations and further categorises them according to the nature of the hazard sources, including shipper, warehouse, apron, customs, and aircraft. Table 1 summarizes the hazard sources associated with air cold chain logistics.

1. Shipper

In international trade, shippers are critical in ensuring the safe transport of goods, particularly in cold chain logistics, where "shipper risk" is a key concern. Shippers must adhere to various service agreements, including shipping time and equipment (Ding et al., 2023). IATA (2024) has noted that shippers and airlines should collaborate to develop effective handling techniques and packaging solutions, especially for temperature-sensitive goods like perishables. As a result, shippers are responsible for precooled cargo, inspecting refrigeration units, and managing quarantine and customs procedures throughout transportation.

However, several risks threaten the integrity of goods during transportation. Poorly designed or manufactured packaging and improper loading can lead to inadequate protection and temperature control (Ding et al., 2023). Vamza et al. (2021) emphasized that inadequate thermal packaging undermines cold chain sustainability (Li et al., 2024). The insulation material, product properties, and cooling agent selection influence the effectiveness of the packaging. Packaging materials and methods directly affect temperature maintenance during transit (Ng et al., 2020). Failing to properly precool or expose goods to unsuitable temperatures can lead to significant product degradation (Wu & Hsiao, 2021; Xu, 2011). According to Zheng et al. (2020) and Li et al. (2024), ineffective precooling can disrupt the entire cold chain, resulting in product spoilage, and is particularly crucial for long-distance shipments of temperature-sensitive items. Andrea Gruber from IATA stressed that shippers must ensure their packaging meets high standards, especially in pharmaceutical shipments, to prevent damage and address potential hazards (Liu, 2024; Sykes, 2018).

Fig. 1. Processes of air cold chain logistics.

2. Warehouse

Shipped items must be delivered to the airline's export warehouse prior to the flight's departure. Before loading onto the aircraft, the goods are processed at the warehouse to consolidate into unit load devices (ULDs), requiring specialized facilities, equipment, and technology to manage temperature-sensitive cargo.

Moreover, this procedure carries significant risks due to insufficient warehouse infrastructure. Mostofa (2024) stated that warehouse infrastructure for storing cargo safety, with its effectiveness closely tied to airport infrastructure quality. The lack of proper cold chain facilities, particularly in low-income countries (Aravindaraj et al., 2020; Kis, 2022), or poorly organized warehouses, can lead to severe degradation in food quality (Khan et al., 2022; Vithu & Moses, 2016). Additionally, risks such as temperature abuse from improper handling and insufficient cooling of products further threaten the integrity of temperature-sensitive goods (Ye et al., 2022). IATA (2025b) further emphasizes that in regions such as Latin America, Africa, and Southeast Asia, where perishable and agricultural exports rely on robust refrigeration systems to maintain product integrity, the importance of reliable cold chain infrastructure becomes particularly evident, while pharmaceutical goods depend on airport-based temperature-controlled storage to maintain product stability.

3. Apron

Before departure, cargo is transferred from the warehouse to air cargo containers on the airport apron, awaiting loading. The apron is one of the highest-risk areas for temperature exposure during loading or unloading. The Medicines and Healthcare Products Regulatory Agency (2019) emphasized that the temperature on the apron can fluctuate drastically, dropping to −50 °C in winter and rising to 50 °C in summer (Chaomuang et al., 2024). These extreme temperatures can severely affect various types of cargo, particularly temperature-sensitive items like pharmaceuticals and perishable goods.

Minimizing apron time (the period between warehouse retrieval and aircraft loading or unloading) is crucial to reducing the risk of temperature variations. Ground handlers must handle and store temperature-sensitive cargo with extreme care, particularly during transit (World Health Organization, 2015). However, human errors, such as prolonged handling times due to inadequate training or knowledge, significantly increase the likelihood of temperature fluctuations (Abou El Hassan et al., 2017; Suwanwong et al., 2018; Wu & Hsiao, 2021). Poor apron equipment conditions can lead to cargo delays and short shipments (Suwanwong et al., 2018), while extended handling increases the risk of product quality and safety issues, potentially causing temperature abuse during loading (Mustafa et al., 2024; Wu & Hsiao, 2021; Ye et al., 2022). Delays in loading and unloading operations or with an indirect flight may result in temperature variations that adversely affect the quality of goods. The extent of these variations may also depend on the availability and advancement of apron equipment, as well as whether sufficient resources are allocated to cold chain operations. Chaomuang et al. (2024) further demonstrated the risks associated with prolonged transportation times, especially when delays on the apron or indirect flights requiring transfers at intermediate airports (e.g., Dubai) expose goods to significant temperature variations. Typhoons and heavy snowfall may further exacerbate delays in this process, increasing cargo exposure to temperature fluctuations. Goods exposed before aircraft loading or during unloading are susceptible to the risk of temperature exposure, which may lead to quality issues and compromise product integrity.

4. Customs

In international cold chain logistics, improper customs documentation can cause significant risks, including delays, unnecessary costs, and compromised product quality and delivery schedules. During transit through airports, goods must pass customs at each stop, and failure to meet customs clearance requirements or experiencing long waiting times can lead to critical delays, making customs a significant hazard source in the cold chain process (Chaomuang et al., 2024).

In-transit goods must undergo security clearance, and if the ULD is opened for inspection, it is essential to minimize the inspection time and quickly secure the doors afterwards (World Health Organization, 2015). IATA (2022) stressed that delays in customs clearance, whether for import, export, transit, or quarantine, can severely disrupt the handling of temperature-sensitive goods. Without proper and timely documentation, the risk of customs delays increases, leading to temperature fluctuations that damage the cargo.

5. Aircraft

Transit duration and ambient temperatures are critical risk factors that directly influence the choice of packaging and energy consumption in cold chain logistics (Rodrigue, 2020). For temperature-sensitive goods like medicines, failure to strategically place cargo—such as near doors or alongside other incompatible cargo—can result in temperature abuse and product damage (Muspratt, 2018). These risks highlight complexities and potential failures in planning and positioning goods during air transport. In addition, poor route planning and inadequate scheduling exacerbate the risks within cold chain logistics. Delays or transportation breakdowns can severely impact product quality, especially when timely delivery is crucial (Demir et al., 2021; Srivastava et al., 2015). These issues underscore the potential for significant losses if transit delays or disruptions occur.

The studies on air cargo have primarily focused on predicting international air cargo volume (Nguyen, 2024), air freight demand (Akinyemi, 2023), the relationship between air cargo and the economy (Karanki et al., 2024; Nguyen, 2023), assessing risks of subcontracting agents (Kulak et al., 2018), and optimizing sustainable operations in air cold chain logistics (Mizrak & Cantürk, 2025). Existing studies related to cold chain delivery mainly focus on product-specific packaging (Liu & Li, 2021; Zhao et al., 2020), equipment and monitoring technologies (Huang et al., 2024; Ye et al., 2022), and overall cold chain management (Pambudi et al., 2022; Qian et al., 2022) to reduce temperature variation risks and preserve product quality. FMEA has been widely applied in exploring food safety risks (Aleksic et al., 2022; Wu & Hsiao, 2021). However, limited studies address risks from the perspective of air cold chain logistics. To fill this gap, this study applies FMEA and a Rule-based Bayesian Network (RBN) to identify and assess critical hazards in air cold chain logistics, aiming to prevent temperature deviations during delivery.

3. Research design and methodology

3.1. Failure modes and effects analysis (FMEA)

FMEA is a proactive method for evaluating processes, identifying pressing problems, and enhancing awareness of risk management (Wu &

Table 1
Hazards of air cold chain logistics.

Hazards source	Hazards	Description	References
Shipper	Poor cooling packaging (S1)	Inadequate cold chain packaging exposes products to extreme ambient temperatures, compromising their stability and efficacy.	Sykes (2018), Ng et al. (2020), Li et al. (2024)
	Incomplete or no temperature data logs (S2)	Incomplete data logging is a barrier to an audit trail and regulatory standards.	Sykes (2018), Liu (2024)
	Wrong cooling agents (S3)	Wrong cooling agents lead to wrong temperature, thus damaging the quality of products during transit.	Vamza et al. (2021), Ng et al. (2020), Li et al. (2024)
	Insufficient pre-cooling (S4)	Insufficient pre-cooling to the desired temperature during long-distance transportation.	Xu (2011), Zheng et al. (2020), Wu and Hsiao (2021), Choi (2023)
Warehouse	Inadequate usage/ improper management of cold storage (W1)	Poor warehouse storage management could reduce products' quality.	Vithu and Moses (2016), Khan et al. (2022), IATA (2025b)
	Insufficient cooling before leaving the warehouse (W2)	Insufficient pre-cooling of products before leaving the warehouse may result in temperature loss while awaiting loading on the apron.	Ye et al. (2022)
	Lack of cold storage and warehousing facilities (W3)	Insufficient facilities or equipment in warehouses to store temperature-sensitive goods and maintain the quality of the products.	Aravindaraj et al. (2020), Kis (2022), Mostofa (2024); IATA (2025b)
Apron	Weather-related delay in waiting time (Ap1)	Apron delays caused by typhoons or extreme weather, including temperature changes.	Chaomuang et al. (2024), Mustafa et al. (2024)
	Delays by poor equipment operations (Ap2)	Delays in loading and unloading operations due to inadequate or outdated equipment.	Suwanwong et al. (2018), Wu and Hsiao (2021), Chaomuang et al. (2024)
	Damage caused by human error (Ap3)	Insufficient knowledge among employees regarding cold chain procedures, coupled with potential damage during loading and unloading operations.	Abou El Hassan et al. (2017), Suwanwong et al. (2018), Ye et al. (2022)
Customs	Long waiting time in customs clearance (C1)	Prolonged waiting times for customs clearance.	Chaomuang et al. (2024)
	Refrigerated containers' temperatures rise due to being opened by customs to check (C2)	The inspection of refrigerated containers, which involves opening them, may impact the quality of the stored products due to the resultant temperature increase.	Chaomuang et al. (2024)
Aircraft	Inappropriate storage location on the plane (A1)	Improper storage locations on the plane, such as those near the door, can lead to temperature increases.	Muspratt (2018), Chaomuang et al. (2024)
	Transit time exceeds estimated time (A2)	The transit time for the aircraft exceeds the estimated duration.	Rodrigue (2020)
	Flight delays (A3)	Flight delays exceeding the estimated temperature control duration.	Srivastava et al. (2015), Demir et al. (2021)

Hsiao, 2021). FMEA has been widely utilized to assess risks in cold chain logistics processes (Aleksic et al., 2022; Liao et al., 2023).

FMEA assigns numerical values to risks associated with potential failures by evaluating three key factors: Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) is then calculated by multiplying these three values: $RPN = S \times O \times D$. However, traditional FMEA faces challenges in addressing uncertainties, particularly when dealing with subjective expert evaluations and imprecise data. To overcome these limitations, researchers have proposed integrating FMEA with advanced methods such as fuzzy logic (Liu et al., 2013), Evidential Reasoning (Yang & Wang, 2015), Bayesian Networks (BN) (Yang et al., 2008) and fuzzy belief RBN (Wan et al., 2019).

In this study, due to the absence of historical data, the three FMEA metrics are defined using linguistic terms to facilitate subjective assessment (Park et al., 2023; Yang et al., 2008). Specifically, Occurrence (O) is categorized into five levels: very low, low, average, high and very high. Severity (S) is assessed across five levels: negligible, marginal, moderate, critical and catastrophic. Detection (D) is evaluated using five levels: highly unlikely, unlikely, average, likely and highly likely. These categorizations culminate in the RPN, which is also expressed using five levels: very low, low, average, high and very high. Detailed definitions for the levels of the three metrics are outlined in Table 2, Table 3, and Table 4, as referenced by Chang et al. (2021).

3.2. FMEA-RBN

FMEA has limitations, including its inability to handle uncertain risk data its reliance on an assumption of equal weighting for all constituent risk metrics. In order to overcome the shortcomings, RBN addresses these limitations by allowing for variations in the expertise and experience of experts through the assignment of different weights. While the Causal Bayesian Network used by Zhu et al. (2021) excels at modeling causal relationships, our FMEA-RBN approach is specifically tailored for systematically prioritizing risks based on the three core FMEA components (S, O, D), which is the primary objective of this study. Similarly, while Kamal and Aydın (2022) applied a fuzzy RBN, our use of a rule-

Table 2
Definition of occurrence for air cold chain logistics.

Occurrence of hazard (O)	Definition
Very Low (VL)	The likelihood of failure occurring at some point during a product's lifespan is low but non-negligible
Low (L)	It is anticipated to occur approximately once annually
Average (A)	A periodic failure (occurring on a quarterly basis)
High (H)	A regularly failure occurring monthly
Very High (VH)	Repeated failures are highly anticipated

Table 3
Definition of severity for air cold chain logistics.

Severity of hazard (S)	Definition
Negligible (N)	Temperature excursion is negligible, but cold chain logistics completed the function to maintain the quality of temperature-sensitive products.
Marginal (MA)	Temperature excursion is marginal, but cold chain logistics completed the function to maintain the quality of temperature-sensitive products.
Moderate (MO)	Temperature excursion is moderate but within range, and cold chain logistics completed the function to maintain the quality of temperature-sensitive products.
Critical (CR)	Temperature excursion is critical, and the quality of temperature-sensitive products is compromised throughout the cold chain.
Catastrophic (CA)	Temperature excursion is catastrophic, and the quality of temperature-sensitive products is compromised throughout the cold chain.

Table 4
The definition of probability of the hazard being undetected for air cold chain logistics.

Probability of the hazard being undetected (D)	Definition
Highly unlikely (HU)	Temperature excursion is highly unlikely to be unnoticed.
Unlikely(U)	Temperature excursion is unlikely to be unnoticed.
Average(A)	Temperature excursion is usually unnoticed.
Likely(L)	Temperature excursion may be unnoticed.
Highly likely (HL)	Temperature excursion is highly likely to be unnoticed.

based framework with Degree of Belief (DoB) provides a more intuitive and structured method for experts to express their uncertainty directly without the added complexity of defining fuzzy membership functions.

Considering the benefits of FMEA and RBN, this research assessed risks of air cold chain logistics with the combination of both methods (FMEA-RBN), as it is particularly suited for modeling uncertain and complex domains. FMEA-RBN has been applied in various studies, primarily within the maritime sector. For instance, Chang et al. (2021) assessed the risk of maritime autonomous surface ships, and Park et al. (2023) applied the methodology to investigate risks related to maritime cybersecurity, providing risk rankings and detailed risk distribution. However, research has yet to apply FMEA-RBN in air cold chain logistics. This study fills that gap and offers a novel perspective for analyzing air cold chain logistics hazards.

The study adapts Park et al. (2023)'s approach and applies it to air cold chain logistics with the six steps as follows:

(1) Identifying hazards in the air cold chain logistics.
(2) Developing a Bayesian network (BN)
(3) Building up a rule-based framework integrated with the Degree of Belief (DoB) in FMEA-RBN.
(4) Employing a Bayesian Reasoning mechanism for the aggregation of rules.
(5) Applying utility functions to transform results into crisp values.
(6) Conducting a sensitivity analysis.

Step 1: Identifying hazards in air cold chain logistics.

Through a comprehensive literature review and analysis of interview data, this study identifies five categories of hazards in the air cold chain logistics: Shipper, Warehouse, Apron, Customs, and Aircraft. Each category includes several hazards. The details of the hazards can be seen in Table 1.

Step 2: Developing a conceptual BN.

The hazard categories and corresponding hazards were employed to construct a conceptual BN model. Fig. 2, constructed by GeNIe (a software specific for BN analysis), shows a BN model proposed by this research, where the hazards are represented by blue ovals (root nodes in the BN model), five hazard categories are depicted by five orange ovals (intermediate nodes in the BN model), and the overall risk is the red oval (lead node).

Step 3: Building up rule-based framework integrated with a DoB in FMEA-RBN.

A rule-based approach is implemented for the BN, employing a set of rules to establish relationships and associated risk levels. These rules explain the relations between the IF and THEN parts of the model, enabling the conversion of p input attributes {A1, A2, …, Ap} (*IF* part) into q possible outcome states {C1, C2, …, Cq} (*THEN* part) through the assignment of a DoB βs (s = 1, 2, …, q) to each state Cs (s (s ∈ q) ∈q).

In this study, a belief structure is utilized to aid in identifying the respondents' comprehension of the particular hazards during the implementation of the IF-THEN rules. Expert judgment, a crucial component in the establishment of rules, can be employed to validate that the rules with belief structures, ensuring they reflect sound reasoning and experience. A DoB distribution of the three parameters (i.e., S, O, and D) is presented in Table 5. With three parameters and five levels of degrees under each parameter, thus 5^3 = 125 rules are identified for each hazard. Here, we use the first rule (R1) and the last rule (R125) as an example to describe the relationship between the parameters and the risk value (V):

R1: **IF** O1, S1, and D1, **THEN** {(1, V1), (0, V2), (0, V3), (0, V4), (0, V5)}.

R125: **IF** O5, S5, and D5, **THEN** {(0, V1), (0, V2), (0, V3), (0, V4), (1, V5)}.

The rules can be explained as follows:

R1: IF the hazard occurrence is very low, severity is negligible, and the probability of the failure being undetected is highly unlikely, THEN the risk level is assigned a 100 % DoB to very low, 0 % DoB to low, 0 % DoB to average, 0 % DoB to high, and 0 % DoB to very high.

R125: IF the hazard occurrence is very high, severity is catastrophic, and the probability of the failure being undetected is highly likely, THEN the risk level is assigned a 0 % DoB to very low, 0 % DoB to low, 0 % DoB to average, 0 % DoB to high, and 100 % DoB to very high.

Step 4: Employing a Bayesian Reasoning mechanism for the aggregation of rules.

A Bayesian Reasoning mechanism is used in aggregating obtained data into the FMEA-RBN model. The IF-THEN rules establish each node's conditional probability table (CPT). The CPT for the hazards (with S, O, and D) is presented in Table 5, providing a comprehensive understanding of the potential risks.

The number of rules and CPT for hazards differs from Table 2 depending on the number of child nodes. For example, 'Warehouse,' 'Apron,' and 'Aircraft' have three hazards, and each should have 5^3 = 125 rules. 'Customs' has two hazards, 5^2 = 25 rules, whereas 'Shipper' has four hazards and should have 5^4 = 625 rules. Furthermore, the overall risk includes five hazard categories, so it should have 5^5 = 3125 rules.

After constructing the model, the marginal probabilities must be calculated by aggregating the prior probabilities. To determine the marginal probability p (Rh) of the outcome, the prior probabilities of all relevant nodes are analysed as follows (Park et al., 2023; Yang et al., 2008):

$$p(Rh) = \sum_{i=1}^{5}\sum_{j=1}^{5}\sum_{k=1}^{5} p\left(RO_i.S_j, D_k\right)p(O_i)p\left(S_j\right)p(D_k), (h = 1, \dots, 5)$$

where h represents the number of states of R.

Step 5: Applying utility functions to transform results into crisp values

As the DoB is a set of utility values (i.e., a distribution combined with

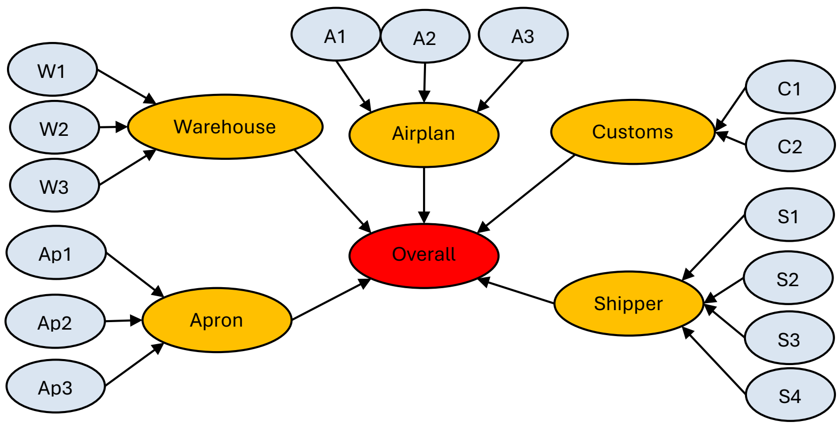

Fig. 2. Conceptual air cold chain logistics BN model.

Table 5
CPT of FMEA-RBN.

O				O1				…				O5			
S		S1		…		S5				S1		…		S5	
D	D1	…	D5		D1	…	D5		D1	…	D5		D1	…	D5
V1	1		0.67		0.67		0.33		0.67		0.33		0.33		0
V2	0		0		0		0		0		0		0		0
V3	0		0		0		0		0		0		0		0
V4	0		0		0		0		0		0		0		0
V5	0		0.33		0.33		0.67		0.33		0.67		0.67		1

the 5-point Likert scale of O, S and D), it should be converted to a crisp value for easy understanding by humans. Based on the 5 levels shown in Tables 2–4, the utility values for O, S and D can be presented as UO1 = US1 = UD1 = 1, UO2 = US2 = UD2 = 2, …, UO5 = US5 = UD5 = 5 (Chang et al., 2021; Park et al., 2023). According to the IF-THEN rules (see Step 3), the combinations of the above 5 levels of O, S, and D were set as:

IF O1, S1, D1, THEN {(1, V1), (0, V2), (0, V3), (0, V4), (0, V5))
IF O2, S2, D2, THEN {(0, V1), (1, V2), (0, V3), (0, V4), (0, V5))
IF O3, S3, D3, THEN {(0, V1), (0, V2), (1, V3), (0, V4), (0, V5))
IF O4, S4, D4, THEN {(0, V1), (0, V2), (0, V3), (1, V4), (0, V5))
IF O5, S5, D5, THEN {(0, V1), (0, V2), (0, V3), (0, V4), (1, V5))

Therefore, the utility values are:
UR1 = UO1*US1*UD1 = 1
UR2 = UO2*US2*UD2 = 8
UR3 = UO3*US3*UD3 = 27
UR4 = UO4*US4*UD4 = 64
UR5 = UO5*US5*UD5 = 125

Thus, the crisp value can be obtained by the following equation:

$$\text{Crisp value} = \sum\nolimits_{z=1}^{t} p(Rh)UR_z$$

where x represents the number of linguistic terms of a node, $p(Rh)$ is the marginal probability, and URz ($z = 1, 2, 3, 4, 5$) denotes the synthesised utility value allocated to the rule. Subsequently, risk values (V) for all hazards and categories are calculated using assigned utility values. These values are presented in crisp form, aiding in ranking the associated risks. It is essential to note that (1) crisp value is between 1 and 125, and (2) higher values indicate greater risk values.

Step 6: Conducting a sensitivity analysis

A sensitivity analysis is subsequently performed to validate the robustness of the model. Sensitivity analysis is a commonly used technique in BN analysis to evaluate the model's reliability in response to parameter changes. It can be conducted in various ways. For instance, some papers used Excel to adjust the percentage of a level (Yang et al., 2008), while more recent papers have used GeNIe software to analyze changes in specific linguistic levels (e.g., Chang et al., 2021; Park et al., 2023; Yu et al., 2020). This study adopts the recent approach to conduct a sensitivity analysis using GeNIe to investigate the impacts of hazards on overall risk. We performed an additional validation step to ensure the robustness of the model by examining two axioms proposed by Jones et al. (2010).

Axiom 1. A variation in the probability of each hazard should induce a corresponding variation in the overall risk.

Axiom 2. Variations in the probability distributions of hazards should maintain a consistent influence on risk values.

The primary methodological contribution of this paper is not the development of a new algorithm, but rather the novel adaptation and application of the FMEA-RBN framework to the domain of air cold chain logistics. To our knowledge, this is the first study to employ this advanced risk assessment technique to systematically analyze the hazards in this specific context. By adapting the approach of Park et al. (2023), we provide a tailored and robust model that fills a critical research gap and offers a practical tool for industry stakeholders.

3.3. Questionnaire design

The study employed a two-stage expert validation process. First, the initial list of 15 hazards identified from the literature was validated for relevance and completeness by two senior industry professionals. Second, following this validation, the main risk assessment questionnaire was administered to a separate group of nine experts specializing in air cold chain operations to evaluate the O, S, and D, of each hazard.

The five hazard sources with 15 hazards (see Table 1) identified from existing studies were further validated by two experts: (1) a veteran in the air cargo contracting industry with over 35 years of experience, having served as the former chairman of the Air Cargo Association in Taiwan, and (2) an expert with more than 25 years of expertise as an international express delivery customs affairs consultant which induces to enhance the validity of risk assessment items.

In the questionnaire, respondents assessed the O, S, and D for each hazard using their DoB. Unlike traditional Likert scales, the DoB approach accounts for respondents' uncertainty, thereby providing deeper insights (Chang et al., 2021). Notably, for each parameter (O, S, and D), the total DoB across all levels must equal 100 %. For example, an expert might evaluate the O of "Waiting time for customs clearance is too long" as 10 % Very Low, 20 % Low, and 70 % Medium. Similarly, they could rate the S as 20 % Negligible, 50 % Marginal, 20 % Moderate, and 0 % Critical, while assessing the D as 100 % Average.

3.4. Respondent's background

Nine experts were invited to participate in an expert questionnaire survey. These nine experts, exclusively dedicated to aviation-related cold chain management, are shown in Table 6. While the sample size of nine experts may seem small, the FMEA-RBN methodology prioritizes the depth and relevance of expert knowledge over statistical power derived from large samples. As shown in Table 6, all participants possess extensive, high-level experience (over 16 years for all, and over 25 for most) specifically in air cold chain logistics, ensuring the high quality and reliability of the elicited data. This focus on targeted expertise is consistent with similar FMEA-RBN studies in specialized domains such as three experts in Yu et al. (2020) and nine in Chang et al. (2021). All nine experts have extensive experience in air cold chain logistics, with eight having over 20 years of practical experience in air cargo transportation. Additionally, some experts hold IATA instructor qualifications, while others are employed by companies that have obtained IATA certifications. Their profound expertise in aviation-related cold chain operations significantly bolsters the foundation of this study. In this study, the inputs from all nine experts were assigned equal weight during the data aggregation process, thus the aggregated DoB can be calculated as:

$$\textit{Aggregated DoB} = \frac{1}{N}\sum_{i=1}^{N} DoB_i$$

Where N is the number of experts and *i* represents each expert

This decision was based on the uniformly high and comparable level of expertise and experience across the expert panel, as detailed in Table 6.

Table 6
Respondents' background.

Expert	Position	Work experience
1	Deputy General Manager in an air cargo terminal, where the company has obtained IATA CEIV Pharma certification.	More than 25 years
2	Deputy General Manager in an air cargo terminal, where the company has obtained IATA CEIV Pharma certification.	16–20 years
3	Senior manager in an air cargo terminal, where the company has obtained IATA CEIV Pharma certification.	More than 25 years
4	Chairman of an air freight forwarder and an IATA Dangerous Goods Instructor.	More than 35 years
5	Customs consultant in an express company and an IATA Dangerous Goods Instructor.	More than 25 years
6	Deputy general manager in an air freight forwarder	More than 20 years
7	Junior manager in an air freight forwarder	More than 20 years
8	Senior specialist in Taoyuan international airport corporation	More than 25 years
9	Junior vice president in an airline services department, where the company has obtained IATA CEIV Pharma certification.	More than 25 years

4. Empirical study

4.1. Results of risk assessment

The risk levels of air cold chain logistics are evaluated using FMEA-RBN as described in Section 3.2. In order to save space, the most critical hazard category 'Shipper' is presented as an example as shown in Fig. 3. The CPT for Shipper is presented in Appendix 1. After aggregating expert opinion, the O value of 'Poor cooling packaging (S1)' is around 3.41, with the following DoB: 31 % of VH, 27 % of H, 6 % of A, 28 % of L, and 11 % of VL (see Fig. 3). The S value for S1 is 4.20 (DoB: 50 % of CA, 19 % of CR, 31 % of MO, 0 % of MA, and 0 % of N); whereas the D value is 2.86 (DoB: 11 % of HL, 31 % of L, 14 % of A, 21 % of U, and 23 % of HU).

The values input into the BN are utilized to analyze the risk associated with the hazards for the 'Shipper'. The risk value (illustrated as 'value' in Fig. 3) of the S1 hazard is 60.65, followed by S4 (45.69), S3 (42.33) and S2 (39.40), and the risk for 'Shipper' is 47.43.

Table 7 shows the results of applying the same method to other hazards and sources. The results show that 'Shipper' has the highest risk value (47.43), followed by 'Aircraft' (37.91) and 'Apron' (37.64). When considering each hazard separately, the top three hazards are 'Poor cooling packaging' (S1) (risk value: 60.65), 'Flight is delay' (A3) (risk value: 40.09), and 'Insufficient pre-cooling' (S4) (risk value: 45.69). Fig. 4 further presents the rank of hazards based on the results of Table 7. Risk value higher than 40 is highlighted in red, between 30 and 40 is highlighted in yellow, and lower then 30 is highlighted in green.

4.2. Sensitivity analysis for validation

Validating BN-based models is essential to ensure their robustness and the reliability of the results, especially when conclusions are derived from subjective judgments. This validation process enhances the credibility and acceptance of the model (Chang et al., 2021; Park et al., 2023; Yu et al., 2020).

This study used the software of GeNIe to conduct a sensitivity analysis. The sensitivity analysis focuses on the VH and VL states of the overall risk, as these represent the most extreme and therefore most critical outcomes for risk management. Understanding which individual hazards have the greatest influence on producing a catastrophic failure (VH) or a highly successful outcome (VL) provides the most actionable insights for practitioners seeking to mitigate risks. The results are illustrated in Fig. 5 (when addressing VH in the overall risk) and Fig. 6 (when addressing VL in the overall risk). For example, Fig. 5 shows that setting C1's VH state probability to 100 % (unchanging other hazards) increases the VH state probability of the overall risk to 22.36 % (the end of the green bar), while reducing C1's VH state probability to 0 % decreases the overall risk to 12.36 % (the end of the red bar). This indicates that C1 has a significant impact on the overall risk assessment. In this process, the setting of C1 is changed from 0 % 'very high' to 100 % 'very high' with a step of 10 %. This implies that the impact on the target node "overall risk" (see Fig. 2, the red oval) consistently increases with each change, which aligns with Axiom 1 proposed by Jones et al. (2010). Similarly, S1 (see last bar in Fig. 4) has the lowest impact. On the other side, we can see that when setting the VH state of individual hazard to 100 %, C2 contributes the most and will lead to the VH overall risk of 23.45 %, whereas when setting VH to 0 %, A3 affects the overall risk the most (12.05 % of 'very high').

Fig. 5 shows that in the context of VH, C1 and C2 significantly impact the overall risk. This result indicates that 'Customs', as the category of C1 and C2, could significantly increase the VH of overall risk. This result is because the VH of C1 and C2 are much lower than other threats, and the VH of overall risk would primarily increase once C1 and/or C2 set the VH as 100 %. Conversely, S1 has the lowest impact on the overall risk, this indicates that the 'Poor cooling effect of packaging from shippers' poses a relatively minor risk compared to higher-ranked hazards. Because the VH of S1 is already very high (31 % in Fig. 3), there is

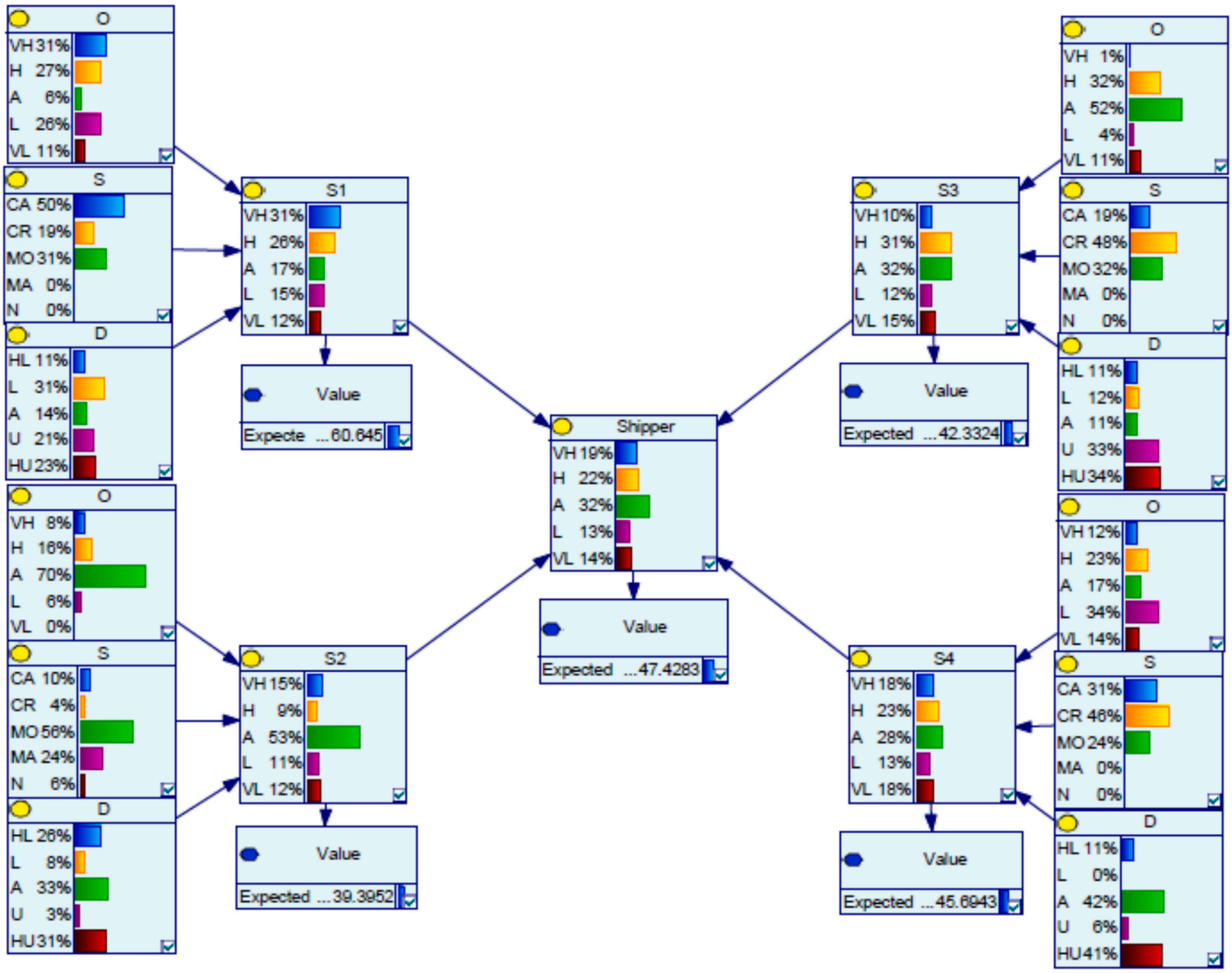

Fig. 3. Result of the hazard category 'Shipper'.

Table 7
Risk values of hazard sources and hazards.

Hazards source	Risk of hazard source	Hazard	VH	H	A	L	VL	Risk of hazard	Rank
Shipper	47.43	S1	31%	26%	17%	15%	12%	60.65	1
		S2	15%	9%	53%	11%	12%	39.40	7
		S3	10%	31%	32%	12%	15%	42.33	6
		S4	18%	23%	28%	13%	18%	45.69	3
Warehouse	33.33	W1	10%	17%	45%	17%	11%	37.36	8
		W2	14%	3%	25%	32%	26%	28.86	12
		W3	12%	15%	27%	27%	19%	33.92	9
Apron	37.64	Ap1	19%	20%	27%	17%	18%	45.13	4
		Ap2	14%	29%	23%	15%	18%	44.14	5
		Ap3	8%	0%	41%	30%	21%	23.76	13
Customs	22.85	C1	14%	1%	16%	41%	27%	22.67	14
		C2	3%	7%	22%	49%	18%	19.03	15
Aircraft	37.91	A1	7%	22%	23%	34%	15%	32.10	11
		A2	13%	3%	48%	18%	18%	32.72	10
		A3	26%	14%	21%	19%	20%	49.02	2

less space when we set the VH of S1 as 100 % compared to others.

When addressing the 'very low' (VL) of overall risk, we should note here that the higher the VL, the lower the overall risk. Fig. 6 shows that the top hazard influencing the VL of overall risk is C2, with values between 26.73 % (the end of the green part) and 16.84 % (the end of the red part).

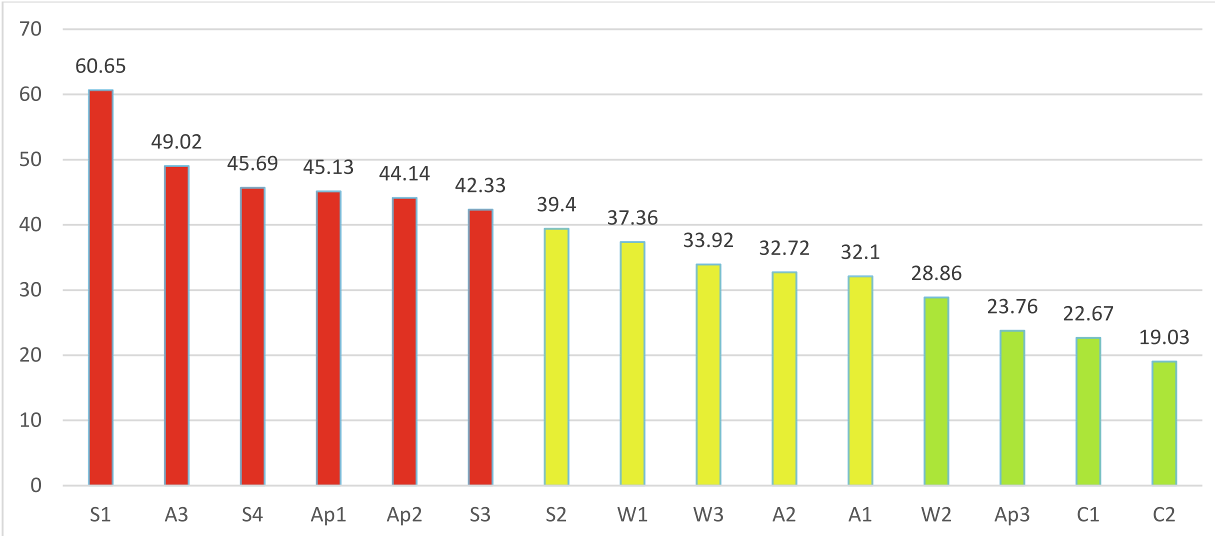

Fig. 4. Rank of hazards.

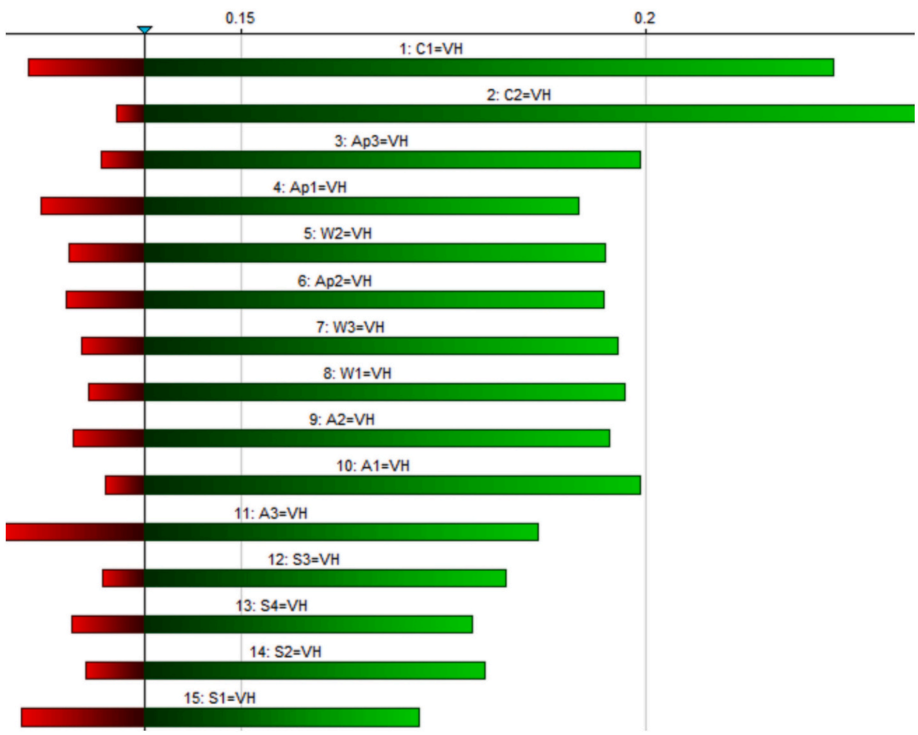

Fig. 5. Sensitivity analysis results with VH overall risk.

The results further reveal two critical scenarios affecting the overall risk: (i) C2 significantly decreases the overall risk with the 'very low' state contributing to 26.73 % (the end of the green part), and (ii) C1 primarily increases the overall risk with the 'very high' state to 15.88 % (the end of red part). Additionally, Fig. 5 illustrates that among the 15 hazards, the limited positive impact of S4 indicates that it is not a very low overall risk.

To verify Axiom 2, a 10 % positive adjustment was applied to the probabilities of the most significant variables (i.e., five hazard categories) (Mohsendokht et al., 2025). These adjustments were made in accordance with their relative importance, as determined through ranking. The resulting changes in the probability of the target node (i.e., overall risk) were then examined. Table 8 presents the initial distribution of overall risk in the second column, while the subsequent columns display the cumulative probabilities following the increase in the prior probabilities of other nodes. The results indicate that elevating the prior probabilities of the hazard category nodes consistently leads to an increase in the posterior probabilities of the target node. This finding is fully consistent with Axiom 2, confirming the robustness and validity of the proposed RBN model for analyzing risks in air cold chain logistics.

4.3. *Implications*

This study examines the risks associated with five key control points in air cold chain logistics. Among these, the 'shipper' emerges as the highest risk contributor, followed by aircraft, apron, warehouse, and

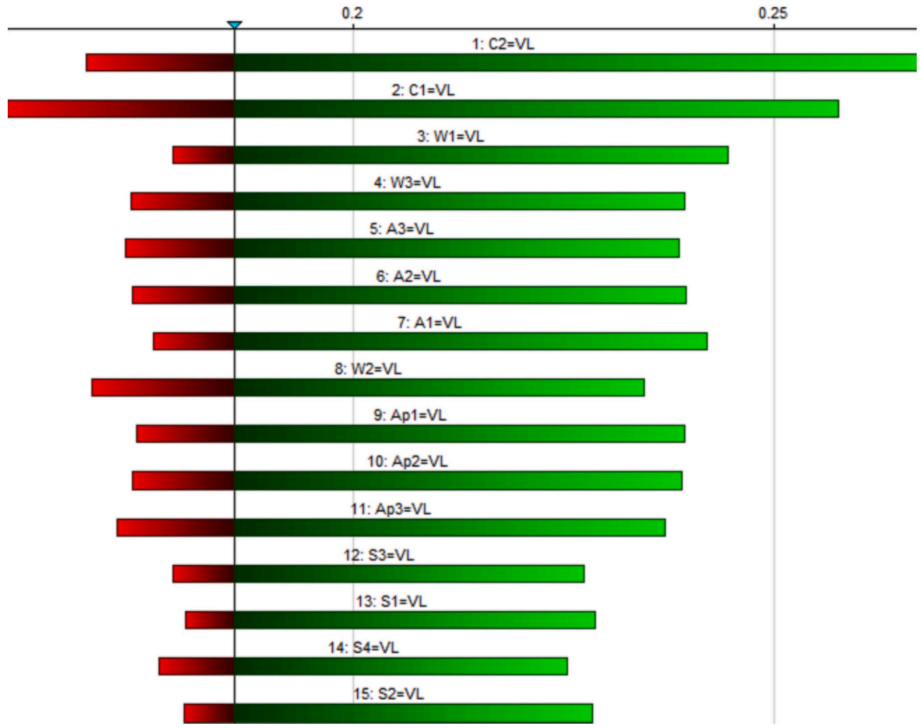

Fig. 6. Sensitivity analysis results with VL overall risk.

Table 8
Results of minor changes in hazard categories.

Customs	–	+10 %	+10 %	+10 %	+10 %	+10 %
Warehouse	–	–	+10 %	+10 %	+10 %	+10 %
Apron	–	–	–	+10 %	+10 %	+10 %
Aircraft	–	–	–	–	+10 %	+10 %
Shipper	–	–	–	–	–	+10 %
Overall						
VH	13.8	14	14.2	14.5	14.8	15.2
H	13.7	13.8	14.1	14.4	14.6	15.1
A	28.8	29.2	29.8	30.4	31.0	31.6
L	25.1	26	26.5	26.8	27.3	27.5
VL	18.6	18.9	19.2	19.5	19.8	20.1

customs risks. To ensure the overall stability of cold chain logistics, it is essential to recognize the interactions among these risk factors. Based on these findings, several recommendations are proposed.

Recommendations are proposed for shippers, who were identified as the highest-risk stakeholders in this study, with Poor Cooling Packaging (S1) being the most critical factor, followed by Insufficient Pre-cooling (S4). As Al Sakhawy et al. (2025) indicate, the lack of standardized practices among supply chain stakeholders results in operational inconsistencies and quality risks. Therefore, this study suggests that shippers should establish standardized operating procedures (SOPs) for pre-cooling and packaging to ensure consistent performance throughout the cold chain process. In addition, shippers should adopt validated thermal packaging solutions and select appropriate refrigerants based on anticipated transit durations and environmental conditions. Given their detailed knowledge of product sensitivities, shippers are responsible for ensuring proper packaging, accurate labeling, and comprehensive documentation. Proactive risk mitigation strategies are also essential, including developing alternative routing plans and integrating temperature loggers to enable real-time monitoring and timely intervention in the event of deviations. Furthermore, effective communication with air service providers is critical to ensuring cargo protection throughout transit. To strengthen accountability and service reliability, shippers are encouraged to establish long-term partnerships with carriers that provide certified temperature-controlled services and performance-based contracts.

Recommendations are proposed for aircraft, which were identified as the second most critical hazard source in this study, with Flight Delays (A3) posing a particularly serious challenge. In the air cold chain process, delays can easily disrupt temperature control, leading to compromised product quality or spoilage, ultimately rendering goods unusable. This study highlights that flight delays significantly heighten risks for time-sensitive products, not only affecting transit times but also creating bottlenecks in ground handling operations, which, in turn, exacerbate risks at the next control point—apron operations. Therefore, this study suggests that airlines should prioritize cold chain shipments in scheduling algorithms and allocate time-sensitive cargo to earlier slots during high-traffic periods to minimize the likelihood of delay-induced temperature deviations. Furthermore, enhanced coordination with ground handling teams can help reduce cargo dwell time and prevent unnecessary exposure to fluctuating ambient conditions. Airlines are also encouraged to adopt cargo-specific predictive analytics tools that integrate weather forecasts, historical delay data, and airport congestion information to proactively reschedule or reroute flights when potential disruptions are anticipated. In addition, establishing clear communication protocols between airline operations and ground handlers is vital to ensure rapid response and continuous temperature protection throughout the logistics process. By implementing these measures, airlines can strengthen cold chain reliability and ensure the integrity of temperature- and time-sensitive goods during air transport.

Recommendations are proposed for apron operations, which were identified as the third most critical hazard source, with weather-related delays in waiting time (Ap1) and delays due to poor equipment operations (Ap2) being particularly important. As Brecht et al. (2019) note, goods left on pallets or in ULDs are susceptible to extreme temperature deviations, with sun exposure potentially raising temperatures by 20–40 °C above ambient. Advanced airports, such as Frankfurt, utilize temperature-controlled vehicles to ensure seamless cold chain transfer; however, many countries still lack such infrastructure. It is recommended that these countries adopt international best practices and invest in similar systems. IATA should also consider establishing verification mechanisms for such temperature-controlled equipment to ensure global consistency and compliance. Moreover, all critical control points—including apron handling and ULD build-up—should follow SOPs with clearly defined accountability. Annual cold chain KPIs for temperature exposure and extreme weather contingency plans are also essential to ensure quality and timely delivery.

Recommendations for policy and regulatory support are proposed. Governments and regulatory bodies should enforce stricter industry standards to ensure compliance with best practices for handling temperature-sensitive goods. Given the significant risks associated with flight delays and apron operations, policies should prioritize the improvement of airport infrastructure, including the expansion of temperature-controlled facilities and the optimization of apron operations to minimize cargo exposure. To address risks arising from unforeseen disruptions, regulatory frameworks should mandate systematic risk assessment protocols, requiring shippers, airlines, and ground handlers to develop contingency plans that address potential cold chain failures. Furthermore, fostering collaboration between public authorities and industry stakeholders is essential to advance technological solutions that enhance real-time risk monitoring, optimize cargo handling efficiency, and mitigate the impact of flight delays and apron-related disruptions on temperature-sensitive shipments.

Finally, IATA (2021, 2025b, 2025c) reported that up to 20 % of temperature-sensitive products are damaged during transit, highlighting persistent vulnerabilities in air cold chain logistics, while rising demand across diverse cargo segments and the growth of e-commerce are driving airports and logistics providers toward automation, digitalization, sustainable infrastructure, and advanced cold chain solutions, emphasizing the importance of effective risk management for resilient and sustainable air cargo operations. Pre-pandemic e-commerce also significantly boosted productivity at high-cargo-volume airports (Karanki et al., 2024), and air transport activity and economic growth in Asia have a bidirectional relationship (Nguyen, 2023). Building on these insights, this study proposes a structured framework for managing risks in air cold chain logistics, targeting the highest-risk control points to improve the integrity and efficiency of temperature- and time-sensitive cargo transport, reduce inconsistencies, prevent spoilage, and strengthen sustainability and competitiveness through waste minimization and economic alignment. Based on the findings of Karanki et al. (2024) and Nguyen (2023), the significance of this research is particularly evident for Taiwan, which ranks tenth globally and third in Asia in terms of air cargo throughput, demonstrating its strategic contribution to regional and global air logistics development.

Overall, although this study focuses on Taiwan and may reflect some regional characteristics, its findings provide valuable insights for enhancing the resilience and efficiency of air cold chain logistics worldwide. Future research incorporating real-time temperature simulations could further enable comparative analyses and broaden understanding of sustainable air cold chain operations.

5. Conclusions and suggestions

5.1. Conclusions

This paper provides a robust assessment of critical hazards associated in air cold chain logistics by utilizing a hybrid approach (FMEA-RBN). Our analysis of 15 hazards, categorized across five hazard sources, definitively establishes the Shipper as the most critical risk contributor, followed by Aircraft, Apron, Warehouse, and Customs. The top three specific hazards identified are the 'Poor cooling effect of packaging' (S1), 'Flight delays'(A3), and 'Packaging and insufficient pre-cooling of cargoes' (S4). This methodological integration of FMEA and RBN constitutes a novel contribution, advancing theoretical risk management frameworks for the temperature-sensitive logistics domain by providing a structure for assessing hazard propagation.

This research reveals that the integrity of the air cold chain is most vulnerable at its very origin with the shipper. The prevalence of risks like 'Poor cooling packaging' (S1) and 'Insufficient pre-cooling' (S4) demonstrates that initial handling failures create vulnerabilities that cascade throughout the entire logistics process, severely exacerbated by systemic disruptions such as 'Flight delays' (A3). Therefore, our findings call for a strategic shift toward proactive, shipper-led quality assurance, strongly supported by robust airline contingency planning and investment in resilient airport infrastructure. For industry consistency, global bodies such as IATA are advised to establish universal certification mechanisms for cold chain systems to guarantee operational standards. Given the paramount role of the shipper, future research should investigate the causal links between specific shipper-side logistical practices (e.g., SOP compliance levels) and overall cold chain risk propagation, ideally utilizing real-time sensor data, to provide more granular managerial guidance.

5.2. Research limitations and suggestions for further research

This study has several limitations that do not undermine the accuracy, foresight, or contributions of the research. The sample size of nine experts, while limited, reflects substantial industry experience, with all participants having over 16 years of expertise. This lends reliability to their insights, though future research should aim for larger sample sizes to enhance industry representation. Furthermore, the expert panel was composed exclusively of professionals based in Taiwan, working with Taoyuan International Airport. While this provides a deep and consistent case-study perspective, it also introduces a potential geographical bias. The risk perceptions and rankings may differ in other regions with different operational environments and regulations. Future research should aim to validate these findings with an international sample of experts, and could benefit from tailoring questionnaires for different national contexts, especially in pre-pandemic scenarios where awareness of risks associated with transporting time and temperature-sensitive goods was limited.

Furthermore, as this study has highlighted the operational vulnerabilities in ground logistics—particularly the absence of temperature-controlled vehicles in certain regions—future research should further examine the performance, feasibility, and cost-effectiveness of implementing such infrastructure. Comparative studies between airports with and without these systems may provide actionable insights. Additionally, investigating how global standards such as those from IATA could guide or incentivize implementation across countries will also support broader cold chain harmonization.

Finally, while this research offers valuable recommendations for risk reduction in air cold chain logistics, future studies could explore the prioritization of these strategies. Identifying additional risk management strategies will assist managers in selecting cost-effective approaches, ultimately enhancing the efficacy of air cold chain operations.

CRediT authorship contribution statement

Chao-Hung Chiang: Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation, Conceptualization. **Chia-Hsun Chang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix 1. CPT for Shipper.

S1	VH											…	VL											
S2	VH					…	VL						VH					…	VL					
S3	VH		…	VL			VH		…	VL			VH		…	VL			VH		…	VL		
S4	VH	…	VL	VH	…	VL	VH	…	VL	VH	…	VL	VH	…	VL	VH	…	VL	VH	…	VL	VH	…	VL
VH	1		0.75	0.75		0.5	0.75		0.5	0.5		0.25	0.75		0.5	0.5		0.25	0.5		0.25	0.25		0
H	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0
A	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0
L	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0
VL	0		0.25	0.25		0.5	0.25		0.5	0.5		0.75	0.25		0.5	0.5		0.75	0.5		0.75	0.75		1

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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