Exploring the Utilization of a Bayesian Network-Based Risk Management System for Cold Chain Packaging

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***Abstract*—This paper presents a comprehensive risk management model for cold chain packaging, as there is still a lack of systematic approaches to address this industry-wide issue. The proposed Bayesian network model is based on literature review and expert opinions of existing cold chain packaging systems to identify various risks and factors. The model includes various components related to the cold chain packaging system. This model can be used by stakeholders such as logistic managers and consultants to weigh the impact of each risk factor and identify potential risks that may affect the effectiveness of the cold chain system. In addition, the model can be used to evaluate the overall effectiveness of the cold chain system and suggest ways to further improve the system. The model will provide valuable insights for industry practitioners to better plan and manage cold chain packaging operations.**

Keywords—cold chain packaging, cold storage, risk management, Bayesian Network

I. INTRODUCTION

There is an increasing demand of cold chain products today due to the advancement of the living standards and health care needs. Cold chain products usually comprise perishable food and pharmaceuticals that require higher standards of transportation and storage than non-perishable items. Cold chains have their own unique characteristics when compared to other supply chains -for example, seasonality in production, and lower temperature transportation and storage [1]. Effectively managing a cold chain is key in order to prevent quality or safety deterioration of products, however, there are a number of issues that must be dealt with. Packaging and packing methods have been identified as one of the primary causes of disruption to the cold chain [2].

Packaging plays an important role along the entire cold chain, from the time of production/processing all the way to the hands of end-users/consumers. There are several levels of supply chain packaging, including primary, secondary, tertiary and quaternary levels[3]. Research on cold chain packaging mostly pertains to the primary level of packaging, which provides basic protection and containment from the environment. However, secondary, tertiary and quaternary levels of packaging can also have great impact on the performance of the entire supply chain. For example, secondary packaging refers to the shipping units, tertiary and quaternary packaging pertains to logistical units, providing extra protection along the cold chain, including the shipping pallets and accessories [4]. The complexity of the cold chain and packaging makes it difficult to find a universal solution for all products. Therefore, it is necessary to assess and manage the uncertainties and risks of the cold chain packaging, in order to mitigate potential and unresolved risks, and ultimately improve the overall cold chain performance [5], [6].

Safety management system is a valuable tool for understanding, evaluating, and managing complex challenges, and can be beneficial in the field of cold chain packaging owing to its intricate and perishable characteristics. Studies of supply chain risk management (SCSM) and cold chain risk management (CCRM) have been conducted and many frameworks and models have been developed [6], [7]. However, risk management of cold chain packaging has not yet been researched in depth. As packaging plays an important role in the overall cold chain performance, assessing the risks associated with it is of utmost importance. Thus, the main objective of this paper is to identify and analyse the risk factors of cold chain packaging and develop a cold chain packaging risk management (CCPRM) model.

The paper is structured as follows: Section 2 provides a literature review on the topic of risk related to cold chain packaging; Section 3 details the research methodology used for constructing the CCPRM model; Section 4 outlines the proposed CCPRM model; and Section 5 contains the conclusion.

II. LITERATURE REVIEW

A. Risk assessment and safety management

First, Cold chain safety management is a process of monitoring and controlling the transportation of temperature-sensitive products from the point of manufacture to the point of sale. This includes maintaining safe temperatures during

the entire journey of the product. The entire system of managing the cold chain process includes steps such as packing of goods, delivery, warehouse storage, and other inter-state regulations. The main objective of cold chain risk management is to ensure the quality of temperature-sensitive products remaining unchanged throughout its journey. By doing so, it helps to maintain the quality of these products, while also ensuring that they are delivered to the end-user in the shortest possible time.

Cold chain risk management involves paying close attention to environmental factors that could affect product quality, such as temperature and humidity. It also involves monitoring the storage, loading and unloading and transportation of temperature-sensitive products. Regular checks and reports are generated based on the data collected from these processes [7]–[9]. Additional policies such as third-party validation and data-driven solutions can be put in place to further strengthen the safety and quality of the cold chain [10]. Third-party validations might include temperature monitoring, product inspection, and tracking the product through each stage of the process. The data-driven solutions could involve fast-response solutions for when products are exposed to extreme cold or heat, as well as analysis of risk factors associated with the product.

Cold chain risk management also includes strict compliance with related regulations and proper documentation of all activities involved in the process [11]. This helps to ensure that all areas of safety management, including temperature control, have been met. The cold chain safety management process must be followed closely to ensure that all temperature-sensitive products are delivered safely and adequately protected. Proper cold chain safety management practices ensure the quality and integrity of the product, while also reducing the risk of injury or illness to people handling them.

B. Bayesian Networks

Bayesian Networks (BN) are a type of probabilistic graphical model that represents a set of variables and their conditional dependencies using a directed acyclic graph (DAG). A Bayesian network is a type of probabilistic graphical model (PGM) that uses Bayesian inference for reasoning under uncertainty [12], [13]. Bayesian network is an ideal tool for resolving uncertainty in any type of application. They provide a compact graphical representation of a probability model, with nodes representing random variables and directed edges (links) representing dependencies between them [14]. As a result, it is well-suited for dealing with conditional reasoning, exploration of cause and effect relationships, and predicting the state of a variable given the state of other variables. The same type of structure can be used to represent any type of complex problem. Bayesian networks are very useful for decision support systems because they allow us to easily compare alternative hypotheses based on their prior probabilities, likelihoods and their joint probability. This is especially important for decision making in areas where data is scarce or inferences need to be made without complete data.

Bayesian networks are also useful for determining how different sources of evidence interact with each other and how they influence the outcome of a decision. This is important when making decisions in complex, uncertain circumstances such as when making predictions about the likelihood of a certain event occurring in the future. In addition, Bayesian networks can help with filtering and sorting data, allowing us to extract the most relevant and accurate set of data to consider when making a decision. Bayesian networks are also very useful in situations where it is difficult to measure the probability of the occurrence of certain events. Overall, Bayesian networks are a powerful and flexible tool for managing uncertainty in decision making and dealing with complex models. They can be used in a variety of applications, including risk assessment, predictive analytics and machine learning.

III. METHODOLOGY

Popular decision-making techniques used in cold chain risk management are Bayesian Network, Failure mode and effect analysis (FMEA), analytical hierarchical process (AHP), fuzzy inference system (FIS), etc [8], [10], [13], [15], [16]. The decision-making techniques used will have an impact on the way the risks are categorised. For example, risk models using AHP will have a hierarchy structure, and risk models using BN will indicate the casual relationships between the risk factors. For studies focusing on supply chain risks, the house of risk (HOR) is often used, and pareto diagrams are drawn to prioritise the risk agents. Also, the method of supply chain operation system (SCOR) in these studies is also used to map out supply chain activities[17], [18]. But these techniques still face limitations. They cannot capture interdependent relationships between risks, the related probabilities and update beliefs with new information. Therefore, BN is selected as the decision-making technique for the risk management model in this study. Some existing literature has already utilized this technique. For studies on fraud risk management in the cold chain, BNs are often used as the decision-making techniques for the model and ‘food fraud types’ is used as the targeted/child nodes. The parent nodes include food categories, year, hazards, notified by, point of adulterants, point of detection, origin or distributed via, action, etc[19], [20].

Since cold chain packaging is a complex system, and interdependencies between risk factors significantly impact the overall performance, which is often overlooked. BN can determine key risks and probabilistic casual relationships. Also, there are not many existing literatures in the field of cold chain packaging, the adoption of BN can help utilize all sources of information. Therefore, BN is chosen to be the decision-making technique used for the cold chain packaging risk management model. BN originates from statistics and artificial intelligence and aims to study the uncertainty in knowledge-based systems. The application of BN includes risk modelling, engineering safety and reliability management, medical diagnosis, etc. It is a probabilistic graphical model for uncertainty modelling that contains nodes and directional arcs pointing between nodes. The directional arcs represent the casual relationships of different nodes, and they are often based on expert opinions. When two nodes are not directly linked to each other, they are assumed to be conditionally independent. The degree of dependence between nodes is represented by conditional probabilities, which is usually determined by expert opinions and data.

The root node’s probabilities are determined by expert opinions. Next, non-root nodes’ probabilities are determined through questionnaires from experts and practitioners in the field. Then the probability value of each node is then determined based on the data derived from expert opinions

and questionnaires. A triangular fuzzy number will be used to account for any linguistic ambiguity.

IV. Proposed Cold Chain Packaging Risk Management Model

A cold chain packaging BN topology is constructed indicating the casual relationships of the risk factors in figure 1. The assigned nodes for the model are shown in table 3, which are derived from literature review. The target node is 'cold chain packaging failure' and has 3 intermediate nodes which are 'external risk', 'network risk' and 'internal risk'. External risks refer to risks outside people's control, which has 3 sub-nodes including natural, political and other emergency disruptions. Network risks refer to risks outside companies' internal control which has 3 sub-nodes including information, supply chain and logistic risks. Internal risks refer to risks inside companies' control which has 1 sub-node, shipping solution selection risk. The root nodes of each sub-node are also specified in table 1.

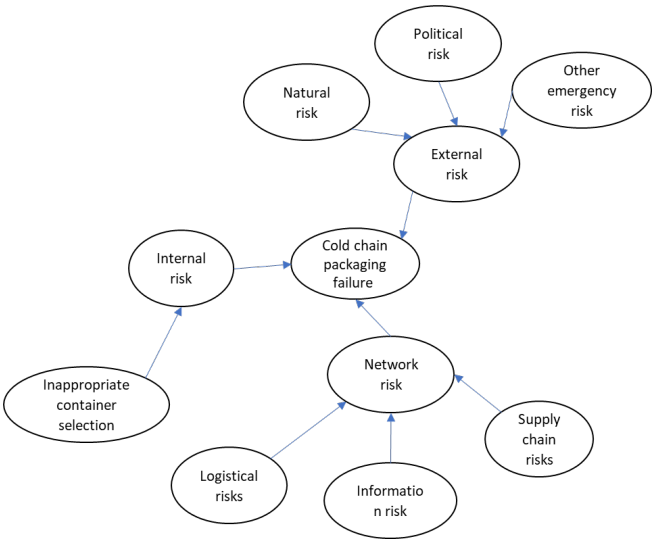

Fig. 1. Topology of the BN based cold chain packaging risk management model

TABLE 1 NODE NAMES OF THE BN BASED CCPRM MODEL

Target node	Intermediate node	Subnodes	Root nodes
Cold chain packaging failure (A)	***External risk (B1)*** [2], [17], [21]–[23]	Natural risk (C1)	Natural disasters (D1), Pandemic (D2)
		Political risk (C2)	Policy changes (D3), Political instability (D4)
		Other emergency risk (C3)	Traffic risk(D5), Power risk(D6)
	Network Risk (B2)[1], [7], [9], [24]–[26]	Information risk (C4)	Lack of awareness of IT (D7), Improper traceability (D8)
		Supply chain risk (C4)	Supply risk (D9), Market/demand risk (D10), Lack of consumer awareness (D11)
		Logistic risk (C6)	Poor/shortage of infrastructure/facilities/equipment (D12), Insufficient temperature & humidity control (D13), Human errors (D14)
		Financial risk (C7)	Fraud(D15), Payment delay(D16)
	Internal risk (B3) [13], [15], [16], [23], [27]	Shipping solution selection risk (C8)	Wrong quantity/capacity selection (D17), Inappropriate phase change materials selection (D18), Inadequate accessories (D19)

V. Conclusion

Failure of cold chain packaging has great impact on the cold chain performance and is one of the main risk factors contributing to cold chain disruptions. This paper reviews the literature on cold chain disruptions and risk management to study the role of packaging in the cold chain and identify risk factors that may potentially cause packaging failure. A cold chain packaging risk management topology model is constructed, and casual relationships of the risk factors are assessed using the Bayesian Network. The risk factors contributing to the cold chain packaging failure are categorised into external, supply chain, logistical, information and shipping solution selection related risks. External, supply chain, logistical and information risks are similar to the risk factors causing cold chain disruptions, while the selection of the shipping solutions are the unique risk factor concerning the cold chain packaging. Inappropriate phase change material selection, capacity and quantity, services and other accessories can lead to cold chain packaging failures.

This paper contributes to the literature by providing new theoretical knowledge in the field of cold chain packaging and can be used as guidelines for industry practitioners. Empirical studies can be conducted to test the model, and the risk categories can be further expanded.

Acknowledgement

This project is partially supported by the European Union's Horizon 2020 Research and Innovation Programme RISE under grant agreement no. 823759 (REMESH).

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