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Reliability Analysis and Optimization of Cold Chain Distribution System for Fresh Agricultural Products

Jinghan Zhang [1,2], Wujun Cao [2] and Minyoung Park [1,*]

[1] Graduate School of Logistics, Inha University, Incheon 22212, Korea
[2] School of Management Engineering, Zhengzhou University, Zhengzhou 450001, China
* Correspondence: mypark@inha.ac.kr; Tel.: +82-32-860-8237

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Abstract: In recent years, with the Chinese government's emphasis on the development of the cold chain logistics market for fresh agricultural products, the rapid development of agricultural cold chain logistics has been promoted in many aspects. However, in the circulation of fresh agricultural products, there is still a serious problem of "broken chain" leading to a high corrosion rate. Therefore, this research has analyzed the uncertain factors affecting the cold chain distribution system based on fault tree model, and then transform it into Bayesian network to evaluate the reliability of the cold chain distribution system for fresh agricultural product, and identify the key factors affecting the reliability of the cold chain distribution system through calculated probability importance of each node. Then we have constructed nonlinear equations with the limit of the cost, based on reliability allocation method to improve the system reliability. Numerical examples are given to validate the proposed models. The optimization result shows that higher reliability value assigned to the factors with high probability importance is more conducive to the improvement of system reliability.

Keywords: cold-chain distribution process; Bayesian networks; probability importance; reliability allocation

1. Introduction

With the continuous development of Chinese economy, people are increasingly demanding the fresher and better-quality agricultural product. However, the cold chain transportation rate of primary agricultural products in China has been lower than developed countries. The cold chain transportation rate of fruits and vegetables, meat, aquatic products are only 15%, 30%, 40%, while the developed countries have reached between 80% and 90%. Even with cold chain transportation, the proportion of "broken chain" in these three kinds of products are as high as 67%, 50%, 42%, while the proportion in developed countries is below 5% [1,2]. According to the statics, Chinese fresh product market has about 280-billion-yuan (about 40.55-billion-dollar) worth of goods lost in transportation every year [3]. Therefore, improving the reliability of cold chain logistics is the key to ensuring the quality of fresh agricultural products and reducing the circulation loss rate. In the cold chain logistics system, the distribution and transportation process occupy about 80% of the time in the entire logistics process [4]. The reliability of the cold chain distribution system reflects the ability to complete the distribution tasks and meet customer demands within the specified time and conditions [5], which will directly affect the quality and safety of fresh agricultural products and customer satisfaction. Therefore, the reliability analysis of cold chain distribution system is of great significance to reduce the circulation loss rate and ensure the quality and safety of agricultural products.

Cold chain logistics of fresh agricultural products means that the agricultural products are kept in a low temperature environment during pre-cooling, packaging, transportation, storage until delivering

to the consumer, to prevent the decay of agricultural products [6]. Barrier and Ruddich first proposed the concept of "Cold Chain" [7]. But until 1940, cold chain logistics began to be valued.

Many scholars proposed principles or theories such as "3T principle" for frozen products [8], "3P theory" and "3C principle" for cooling process [9], "3M principle" and "3Q principle" for cold chain logistics management [10], which lay the foundation for the research of cold chain logistics [11]. Research on the distribution of fresh agricultural products mainly focuses on vehicle routing problem [12–16], location selection of logistics center [17–20], factor analysis and performance evaluation [21–24]. Only a few studies on the reliability of the cold chain logistics system. Zou [25] treated each phase of the food logistics system as a logistics unit and established a safety model of the food logistics system. Guo [26] explored the factors affecting customer satisfaction of cold chain logistics and combined reliability engineering theory with Bayesian network to find out the main factors leading to reduce customer satisfaction.

Bayesian network is a graphical network based on probabilistic reasoning [27], which consists of a directed acyclic graph and a conditional probability table. Maryam [28] proposed a reliability analysis method based on Bayesian network, which combines historical data with expert judgement to handle data scarcity. Cai [29] combined the fuzzy set theory with the Bayesian network model and used it in the reliability analysis of the logistics service system with a large amount of uncertainty information in the system. Reliability allocation is a method often used in system reliability optimization with the expectation that uses the least resource to maximize the whole system reliability through assigns the reliability value to each composing unit in a certain method [30]. Qi [31] combined the reliability analysis with the correlation analysis, sorted the subsystems by TOPSIS method, and then established a reliability allocation model based on structural correlation and failure correlation to optimize the allocation results. Wang [32] studied the reliability of the complex emergency logistics network through simulation analysis.

This research takes the cold chain distribution system of fresh agricultural product as the research object. Firstly, we analyze the factors affecting the reliability of the cold chain distribution system through fault tree model and Bayesian network, and the probability importance is introduced to identify the key factors affecting the cold chain distribution system reliability. Then, we propose an optimization model through combining the reliability allocation method with probability importance and solve it by the particle swarm optimization algorithm. The contribution of this research can help the logistics enterprise of fresh agricultural product to intuitively find the factors affecting its cold chain distribution system reliability and make the decision on how to improve the cold chain distribution system reliability within a limited cost.

2. Modelling Approach

2.1. Factor Analysis of Cold Chain Distribution System based on Fault Tree Model

The normal temperature logistics distribution system consists of logistics functions such as transportation, storage, packaging, loading and unloading, and logistics information management. Compared with room temperature logistics, cold chain distribution system not only pays attention to distribution efficiency and logistics service level, but also guarantees that the goods are in the specified temperature and humidity environment throughout the distribution process. Therefore, cold chain distribution system requires more resource elements. Figure 1 shows a cold chain distribution process and the phases involved.
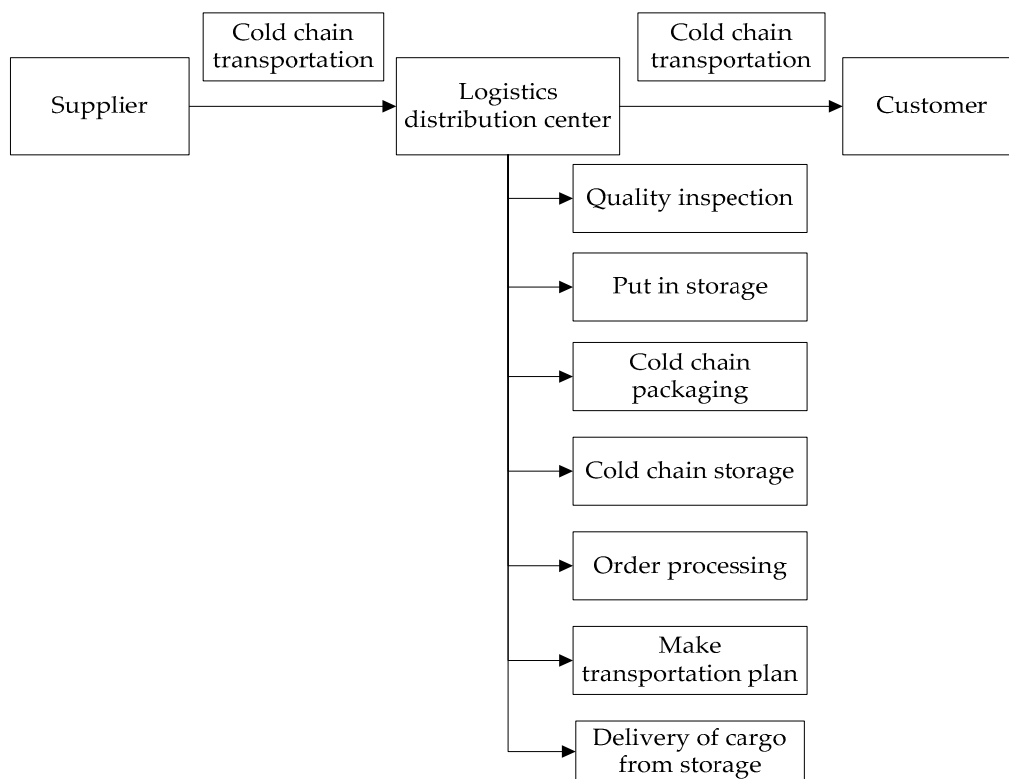
Figure 1. Flow chart of general cold chain distribution.

The failure to complete the logistics goals within the specified time is considered as a failure of the cold chain distribution system, and then all direct causes of failure of the cold chain distribution system are sought:

- Delivery delay: The package cannot be delivered to the designated location within the specified time;
- Quantity and variety inadequacy: Mistakes in sorting process or information errors will result in the quantity or categories of products not meeting the customer's demand;
- Unqualified products: The temperature and humidity are not strictly controlled during transportation or storage, or the product is deteriorated due to cross-contamination between different goods, which could lead to logistics loss of fresh agricultural products.

The cold chain distribution system failure is defined as a top event. The intermediate events are delivery delay, quantity and variety inadequacy, and unqualified products. Since any of these three events will cause the failure of cold chain distribution system, they are connected to the top event by logical OR gates. Then look for the lower-level cause events that cause the intermediate events to occur. According to their logical relationship with the intermediate events, select the appropriate logic gates to connect them with the intermediate events. Follow the above principles until the factors are decomposed to its failure mechanism or probability can be collected by daily events. Figure 2 is the fault tree model of the cold chain distribution system.
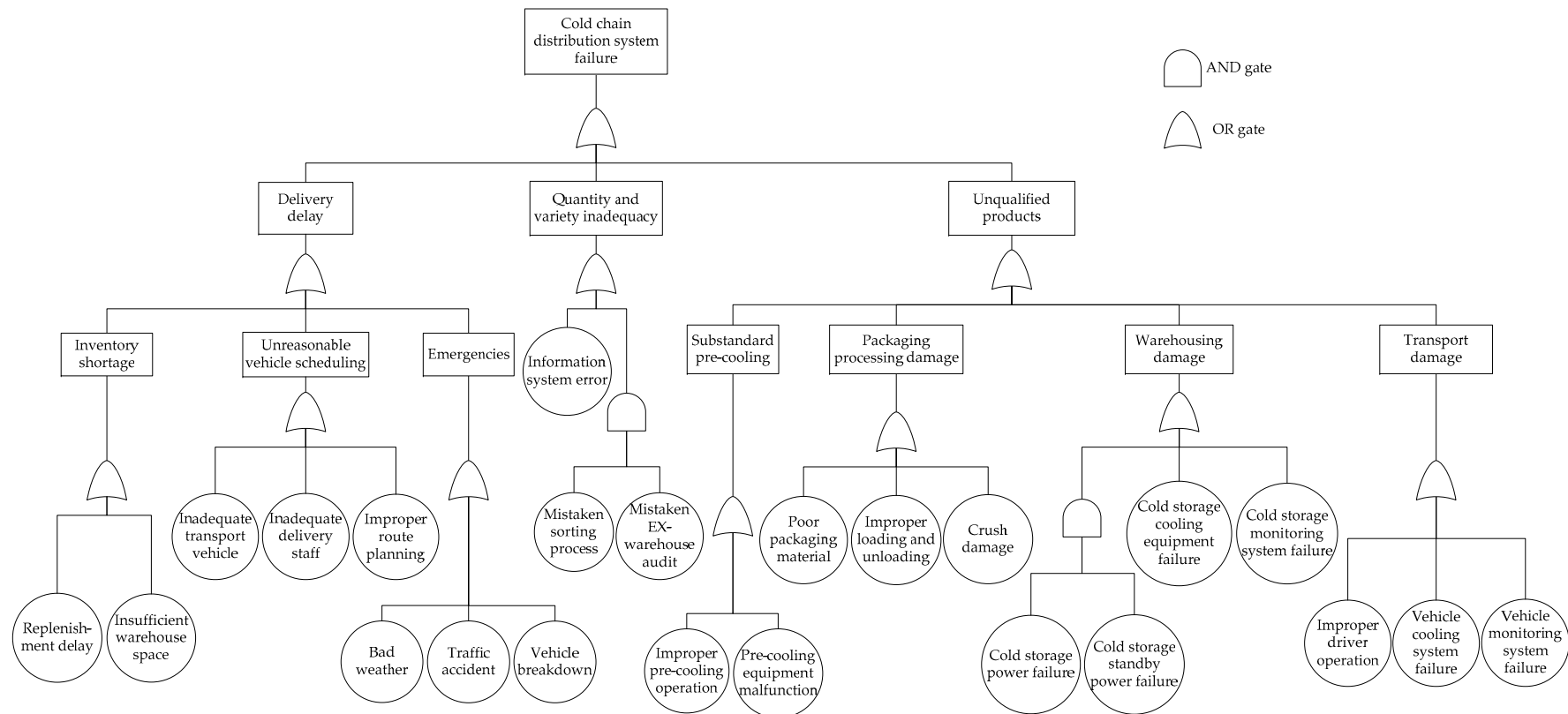
Figure 2. The fault tree model of the cold chain distribution system.

After receiving the customer's order, the logistics center will sort the products from the warehouse. If the information system fails, or the sorting operators pick the wrong category or miss some products, and the inspectors do not review the mistake when the products were moving out of the warehouse. Although these factors will not affect the quality and safety of fresh agricultural products, there is a risk of returns from customers. Due to the short shelf life of fresh agricultural products, the circulation loss rate will increase during the process of returning freight, and the logistics cost of fresh agricultural products will be increased.

The loss of cold chain transportation is mainly caused by the increase of transportation time. It can be divided into three causes: unreasonable vehicle scheduling, vehicle breakdown and emergencies. Table 1 gives the fault causes and analysis in cold chain transportation.

Table 1. Fault causes in cold chain transportation and analysis.

Fault Cause	Specific Reason
Unreasonable vehicle scheduling	Vehicle maintenance and inspection would lead to insufficient transportation vehicles in the logistics center
	Employees take a leave of absence or resignation resulting in insufficient delivery staff
	Unreasonable vehicle route planning
Vehicle breakdown	The driver's improper operation, such as turning off the refrigeration system and monitoring system in order to save electricity and fuel
	Vehicle refrigeration equipment break down
	Vehicle monitoring system break down
Emergencies	Traffic accidents, such as crashes, rollovers, and spontaneous combustion of vehicles during transportation
	Some extreme weather, such as heavy rain, typhoon, or severe haze, which may cause delay for transportation or delivery

Cold chain storage is a logistics activity that uses temperature control facilities to create a suitable temperature and humidity environment for fresh agricultural products to extend the shelf time. If the cold chain storage cannot be accurately controlled, a large amount of logistics loss will be generated, which would also affect the efficiency of the cold chain transportation process. Cold chain storage includes pre-cooling process, cold storage, and packaging. Table 2 shows the fault causes and analysis in cold chain transportation storage.

The fault tree model of the cold chain distribution system can intuitively show the reasons for the system failure and the logical relationship between the various influencing factors. However, the model can only be reasoned from top to down, and its reasoning is limited and not efficient. For a system with many fault events and complex structures, it requires the large amount of calculation and is prone to errors. Therefore, it is converted to a Bayesian network for further inferential calculation.

Table 2. Fault causes in cold chain storage and analysis.

Fault Cause	Specific Reason
Substandard pre-cooling	Failure to timely pre-cooling or operation is not standardized
	Pre-cooling equipment break down
Inventory shortage	As the order volume growth exceeds the forecast, the logistics center cannot replenish the goods in time.
	Due to the limited space of cold storage, the logistics capacity of the logistics center cannot keep up with the order.
Cold storage failure	Power failure in the cold storage, such as power failure, no backup power supply equipment, or backup power supply equipment break down.
	Cold storage refrigeration equipment cannot maintain low temperature environment
	The cold storage monitoring system cannot detect and upgrade the internal environment of the cold storage in real time.
Package damage	Poor packaging materials or the packaging specifications are unreasonable, which will increase contamination of fresh agricultural products
	Violation of operating procedures during loading and unloading, or rough handling, is easy to damage package and fresh agricultural products
	Lack of space planning, or unreasonable space arrangement, the goods are crushed and damaged

2.2. Reliability Analysis of Cold Chain Distribution System based on Bayesian Network

Figure 3 is the Bayesian network of the cold chain distribution system failure by converting the fault tree model constructed in Figure 2 according to the certain rules.
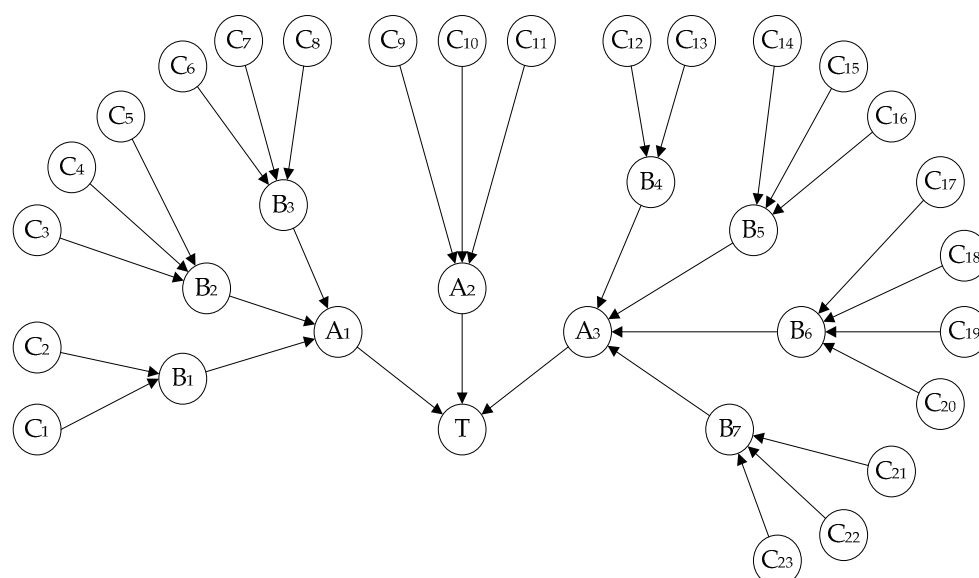

Figure 3. Bayesian network of the failure of cold chain distribution system.

Table 3 shows the node names in Bayesian network in the failure of the cold chain distribution system.

Table 3. Node name in Bayesian network for cold chain distribution system failure.

Node	Node Name	Node	Node Name	Node	Node Name
C_1	Replenishment delay	C_{13}	Pre-cooling equipment malfunction	B_2	Unreasonable vehicle scheduling
C_2	Insufficient warehouse space	C_{14}	Poor packaging material	B_3	Emergencies
C_3	Inadequate transport vehicle	C_{15}	Improper handling of loading and unloading	B_4	Substandard pre-cooling
C_4	Inadequate delivery staff	C_{16}	Crush damage	B_5	Packaging processing damage
C_5	Improper route planning	C_{17}	Cold storage power failure	B_6	Warehousing damage
C_6	Bad weather	C_{18}	Cold storage standby power failure	B_7	Transport damage
C_7	Traffic accident	C_{19}	Cold storage cooling equipment failure	A_1	Delivery delay
C_8	Vehicle breakdowns	C_{20}	Cold storage monitoring system failure	A_2	Quantity and variety inadequacy
C_9	Information system error	C_{21}	Improper driver operation	A_3	Unqualified products
C_{10}	Mistaken sorting process	C_{22}	Vehicle cooling system failure	T	Cold chain distribution system failure
C_{11}	Mistaken EX-warehouse audit	C_{23}	Vehicle monitoring system failure		
C_{12}	Improper pre-cooling operation	B_1	Inventory shortage		

In the Bayesian network, all nodes are represented by x_i *(i=1, 2 … , n)* and the state of each node is represented by (0, 1), then,

$$x_i = \begin{cases} 0, \text{node } i \text{ non} - \text{fault} \\ 1, \text{node } i \text{ fault} \end{cases} \quad i = 1, 2 \cdots n \tag{1}$$

2.2.1. System Reliability

The prior probability of the root node in the Bayesian network is generally obtained through the historical data of the information system and the work log of the operators. When the historical data is sufficiently rich, the frequency of occurrence can be regarded as the prior probability. However, when the data is missing or difficult to count, the prior probability of the root node can be obtained by fuzzy evaluation method.

$$\begin{aligned} P(T = 1) &= \sum_{x_1 \cdots x_n, y_1 \cdots y_m} P(x_1 \cdots x_n, y_1 \cdots y_m, T = 1) \\ &= \sum_{\pi(T)} P(T = 1 | \pi(T)) \times \sum_{\pi(y_1)} P(y_1 | \pi(y_1)) \times \cdots \times \sum_{\pi(y_m)} P(y_m | \pi(y_m)) \times P(x_1) \times \cdots \times P(x_n) \end{aligned} \tag{2}$$

where, $\pi(T)$ means the father nodes of node T, $\pi(y_1, y_2 \ldots y_m)$ means the father nodes of node $y_1, y_2 \ldots y_m$ respectively. So, the reliability of the cold chain distribution system is $R = 1 − P(T = 1)$.

2.2.2. Posterior Probability Inference

In the case where the cold chain distribution system is known to be failure, the probability of each factor causing the system failure can be determined by calculating the posterior probability of each root node.

$$P(x_i = 1 | T = 1) \quad = \frac{P(x_i=1,T=1)}{P(T=1)} \\ = \frac{\sum\limits_{x_1,x_2\cdots x_n,y_1,y_2\cdots y_m} P(T=1,x_1\cdots x_{i-1},x_i=1,x_{i+1}\cdots x_n,y_1,y_2\cdots y_m)}{P(T=1)} \quad (3)$$

Under the condition that the influencing factors are faulted, the probability of the system failure can be judged by calculating the conditional probability.

$$P(T = 1 | x_i = 1) \quad = \frac{P(x_i=1,T=1)}{P(T=1)} \\ = \frac{\sum\limits_{x_1,x_2\cdots x_n,y_1,y_2\cdots y_m} P(T=1,x_1\cdots x_{i-1},x_i=1,x_{i+1}\cdots x_n,y_1,y_2\cdots y_m)}{P(x_i=1)} \quad (4)$$

2.3. Reliability Allocation of Cold Chain Distribution System for Fresh Agricultural Products

The reliability cost function describes the functional relationship between the reliability and cost of the system, including the human resources, materials and financial resources needed to improve the reliability of the unit. In order to solve this problem, scholars have proposed a generalized reliability cost function [33], which has the following properties:

If $0 \le R_i^{(1)} \le R_i^{(2)} \le R_i^{(3)} \le 1$, $C_i(R_i^{(1)}, R_i^{(2)})$ indicates the cost of reliability of i-th unit, R_i increasing from $R_i^{(1)}$ to $R_i^{(2)}$, then:

- $C_i(R_i^{(1)}, R_i^{(2)}) \ge 0$, which means the cost of improving the reliability should be non-negative;
- $C_i(R_i^{(1)}, R_i^{(3)}) = C_i(R_i^{(1)}, R_i^{(2)}) + C_i(R_i^{(2)}, R_i^{(3)}) \ge 0$, which means the cost of improving the reliability from $R_i^{(1)}$ to $R_i^{(3)}$ is same as the cost of the of improving the reliability from $R_i^{(1)}$ to $R_i^{(2)}$ and from $R_i^{(2)}$ to $R_i^{(3)}$;
- $C_i(R_i)$ is a monotonically increasing function, and the higher value of reliability improvement, the higher the cost;
- The cost will be infinite if the reliability is increased to 1.

According to the characteristics of the generalized reliability cost function, foreign scholars proposed a reliability cost function based on feasibility.

The reliability cost of unit i is $C_i(R_i, f_i, R_{i,min}, R_{i,max})$, then

$$C_i(R_i, f_i, R_{i,\min}, R_{i,\max}) = e^{(1-f_i) \times \frac{R_i - R_{i,\min}}{R_{i,\max} - R_i}} \\ R_{i,\min} \le R_i \le R_{i,\max} \quad (5)$$

where, f_i indicates the feasibility of improving the reliability of the unit i, and its value is between 0 and 1. The larger the value is, the greater the feasibility of improving the reliability of the unit. $R_{i,max}$ indicates the maximum reliability value that the unit i can be achieved according to the prior art. $R_{i,min}$ indicates the current reliability value of unit i; R_i is the reliability value assigned unit i with a value range between $R_{i,max}$ and $R_{i,min}$.

Feasibility refers to the difficulty of improving system reliability. For the quantification of feasibility, many studies have adopted the weighting factor method. This research determines the feasibility of each factor from the three aspects: the degree of standardization, the difficulty to detect the fault and maintainability. The weight of the feasibility indicators and each index of factors are scored by experts based on the below tables [34]. Table 4 shows the definition of the judgement matrix, which a_{ij} indicates the degree of impact on the cost between the i-th indicator and the j-th indicator.

Table 4. Definition of judgment matrix.

Relative importance a_{ij}	Interpretation
1	Factor i is as important as j
3	Factor i is slightly more important than j
5	Factor i is more important than j
7	Factor i is significantly more important than j
9	Factor i is absolutely important than j
2,4,6,8	Between two important levels

Get the judgment matrix

$$A = (a_{ij}) = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \tag{6}$$

Calculate the weight vector $W = (w_1; w_2 \cdots w_n)$ and the largest eigenvalue $\lambda_{\max}$ of matrix A, and check the perform consistency on matrix A, calculate the consistency index is $CI = \frac{\lambda_{\max} - n}{n - 1}$. Then calculate the consistency ratio $CR = \frac{CI}{RI}$ according to the random consistency index RI in Table 5. If $CR < 0.1$, then matrix A meets the consistency requirement. On the contrary, the expert needs to re-rate (Table 6).

Table 5. RI value table.

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Table 6. Score criteria of the feasibility indicators.

Factor \ Score	1-2	3-4	5-6	7-8	9-10
Standardization level (S$_1$)	High	Slightly high	general	Slightly low	low
The difficult of fault detection (S$_2$)	Easy	Slightly easy	general	Slightly difficult	difficult
Maintainability (S$_3$)	High	Slightly high	general	Slightly low	low

The weighted sum is obtained by scoring the three indicators of each factor to obtain the total score A_i of the factors:

$$A_i = w_{i1} \times S_{i1} + w_{i2} \times S_{i2} + w_{i3} \times S_{i3} \tag{7}$$

and the feasibility is

$$f_i = \frac{1}{A_i} \tag{8}$$

According to the analysis in the last section. The factors with higher probability importance have greater impact on the system reliability. Therefore, more attention should be paid to the factor with high probability importance during the optimization. That is to say, it should spend more resources to optimize the factors with high probability importance. So, this paper combines the probability importance with the constraint of reliability allocation, and proposes the reliability cost function,

$$C_i(R_i, f_i, R_{i,\min}, R_{i,\max}) = e^{(1-f_i) \times \frac{R_i - (1 + I^{\mathrm{Pr}'}(i)) \times R_{i,\min}}{R_{i,\max} - R_i}} \tag{9}$$
$$(1 + I^{\mathrm{Pr}'}(i)) \times R_{i,\min} \leq R_i \leq R_{i,\max}$$

$I^{\mathrm{Pr}'}(i)$ is the normalized probability importance of the unit i, which is between 0 and 1. It can be seen from the equations that for factors with higher importance, the lower limit of the reliability value assigned is higher than the factor with lower importance.

3. Numerical Example and Results

3.1. Reliability Analysis of Cold Chain Distribution System for Fresh Agricultural Product

Based on the reference [26], this research combines expert opinions to obtain the prior probability of the root node with faulted state in the Bayesian network, as shown in Table 7. In the actual circulation, even the influencing factors are faulted, it does not necessarily lead to the cold chain distribution system failure. For example, when the pre-cooling operation is not standardized, there is a possibility that the fresh agricultural products are not rotten. Therefore, in constructing the conditional probability table of intermediate nodes in the Bayesian network, this research adjusts some conditional probability table based on the fuzzy evaluation method. Not all the intermediate nodes' conditional probability tables are transformed according to the logic gated in the fault tree. Appendix A gives the conditional probability table for each intermediate node and leaf node.

Table 7. Prior probability, posterior probability and probability importance of each root node.

Node	Prior Probability	Posterior Probability	Probability Importance
C_1	0.0259	0.0555	0.2715
C_2	0.0137	0.0432	0.5042
C_3	0.0323	0.1067	0.5506
C_4	0.0267	0.0616	0.3104
C_5	0.0386	0.0850	0.2889
C_6	0.0236	0.0664	0.4293
C_7	0.0361	0.1132	0.5124
C_8	0.0053	0.0162	0.4776
C_9	0.0012	0.0052	0.7697
C_{10}	0.0225	0.0239	0.0145
C_{11}	0.0189	0.0203	0.0173
C_{12}	0.0419	0.1031	0.3526
C_{13}	0.0168	0.0727	0.7819
C_{14}	0.0342	0.1130	0.5515
C_{15}	0.0317	0.0836	0.3906
C_{16}	0.0125	0.0348	0.4182
C_{17}	0.0168	0.0060	0.0478
C_{18}	0.0342	0.0635	0.0038
C_{19}	0.0317	0.0397	0.5038
C_{20}	0.0125	0.0253	0.1541
C_{21}	0.0168	0.1212	0.5365
C_{22}	0.0342	0.1183	0.7109
C_{23}	0.0317	0.0405	0.3874

The probability of failure of the cold chain distribution system is:

$$P(T=1) = \sum_{C_1,C_2\cdots C_{23},B_1,B_2\cdots B_7,A_1,A_2,A_3} P(C_1,C_2\cdots C_{23},B_1,B_2\cdots B_7,A_1,A_2,A_3,T=1)$$
$$= 0.2312 \tag{10}$$

Therefore, the reliability of the cold chain distribution system is $R = 1 - P(T=1) = 1 - 0.2312 = 0.7688$, that is, at the current level, the probability of normal operation of the system is 76.88%, and there is a 23.12% probability that the cold chain distribution system cannot complete the scheduled delivery task within the specified delivery time.

Then the posterior probability value and probability importance value of each node are calculated according to Equations (3) and (4), as shown in Table 7, and Figure 4 shows the comparison between them.
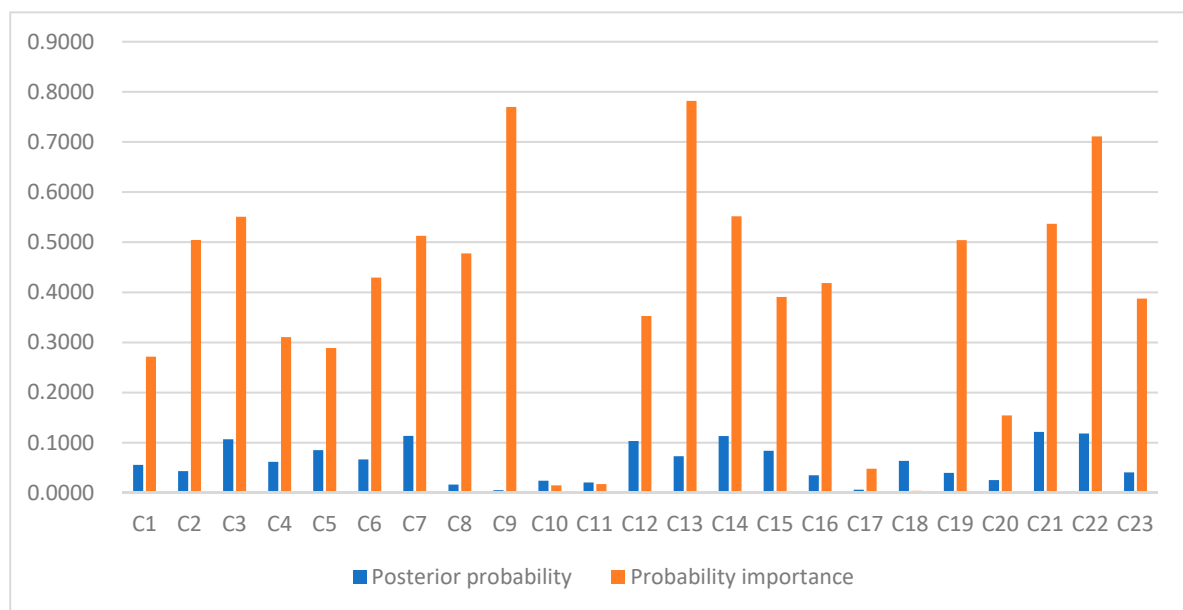
Figure 4. Comparison of prior probability and posterior probability of each root node.

As can be seen from the above figure, the probability importance of the root nodes C_{13}, C_9, C_{22} are relatively high, which means, pre-cooling equipment breakdown, information system error and vehicle refrigeration equipment breakdown are the key factors affecting the reliability of the cold chain distribution system. By comparison, it can be found that the main factors leading to the failure of the cold chain distribution system do not necessarily have a great impact on system reliability. Therefore, the posterior probability is suitable for the purpose of detecting system malfunction, and the probability importance is more suitable as a basis for judging the reliability of the system.

3.2. Reliability Allocation of Cold Chain Distribution System for Fresh Agricultural Product

In the Bayesian network of cold chain distribution system failure, since the bad weather, traffic accidents and vehicle breakdown are emergency events that cannot be subjectively assigned reliability value, these three factors are removed. Then, the minimum reliability value $R_{i,min}$ for each factor is set to 0.85, the maximum reliability value $R_{i,max}$ is set to 0.99, and the expected system reliability value R^* is set to 0.80. The scores of the three indicators are shown in Appendix B.

According to Equations (5) and (9), combined with particle swarm optimization algorithm, the optimal results can be obtained by MATLAB. Table 8 shows the allocation results based on the feasibility and probability importance.

It can be seen from the table that although the optimization results of the two methods have reached the expected system reliability, the cost of adopting the optimization model based on probability importance is lower than the other one, which proves the feasibility and effectiveness of the model based on probability importance.

Table 8. Basic parameters and comparison of allocation results for each node.

Node	Feasibility	Probability Importance	Reliability before Optimization	Allocation Result Based on Feasibility	Allocation Result Based on Probability Importance
C_1	0.20	0.272	0.9741	0.97682	0.97577
C_2	0.18	0.504	0.9863	0.9767	0.97618
C_3	0.17	0.551	0.9677	0.97679	0.97572
C_4	0.22	0.310	0.9733	0.97688	0.97529
C_5	0.15	0.289	0.9614	0.97662	0.97561
C_9	0.17	0.770	0.9988	0.9775	0.98058
C_{10}	0.23	0.015	0.9775	0.9757	0.97411
C_{11}	0.28	0.017	0.9811	0.97587	0.97552
C_{12}	0.24	0.353	0.9581	0.97675	0.97603
C_{13}	0.19	0.782	0.9832	0.97799	0.97999
C_{14}	0.29	0.551	0.9658	0.97657	0.976
C_{15}	0.33	0.391	0.9683	0.97692	0.9756
C_{16}	0.25	0.418	0.9875	0.97677	0.97493
C_{17}	0.17	0.048	0.9950	0.9759	0.97515
C_{18}	0.23	0.004	0.9375	0.97575	0.9751
C_{19}	0.16	0.504	0.9874	0.97737	0.97491
C_{20}	0.23	0.154	0.9847	0.97639	0.9759
C_{21}	0.26	0.536	0.9625	0.97687	0.97539
C_{22}	0.18	0.711	0.9703	0.97709	0.98106
C_{23}	0.22	0.387	0.9847	0.97681	0.9747
System reliability			0.7688	0.80001	0.80004
Reliability cost				418.3101	261.561

4. Discussions

Through the analysis in the previous section, the first three nodes with the highest probability importance are C_{13}, C_9 and C_{22}. In the feasibility-based reliability allocation method, the nodes C_{13}, C_9 and C_{19} are assigned the highest reliability value, which is 0.97799, 0.9775, and 0.97737, respectively. While the reliability allocation method based on the probability importance assigns the highest reliability to the nodes C_{22}, C_9 and C_{13}, which is 0.98106, 0.98058 and 0.97999. Although the former method has also assigned relatively high reliability to the nodes C_{13} and C_9, the reliability assigned to all factors are at the same unit level, and the difference is not large. However, the reliability allocation model based on the probability importance assigned the higher reliability to the factors with higher probability importance while improving the reliability of other factors. Therefore, when the reliability of the system satisfies the reliability index, the reliability allocation method based on probability importance requires less cost.

Comparing the reliability allocation results, based on probability importance with the reliability of each factor before optimization, it is found that the reliability values of nodes C_{16}, C_{17} and C_{19} are lower than those before optimization. This is because the probability importance of these three nodes is low, so it is assigned relatively low reliability value to the nodes. Although both two allocation methods assign a relatively high reliability value for node C_9 (i.e., information system errors), they are still lower than the values before optimization. This is due to the high reliability of the node before optimization. The cost will increase greatly if it keeps assigning higher reliability to this node, but the improvement of the system reliability is not obvious. Therefore, for enterprises, the reliability improvement of cold chain distribution system has basically dynamic characteristics, and it would be better to calculate the probability importance value again after optimization.

5. Conclusions

In this research, the fault tree model of the cold chain distribution system of fresh agricultural products is constructed and transformed into Bayesian network to evaluate the reliability of the system. Then, we identify the key factors affecting the system reliability through calculating the probability importance, while previous researches only compared the posterior probability value to decide the key

factors affecting the system reliability. Through comparing the posterior probability value and the probability importance, it shows that the posterior probability is suitable for the purpose of detecting system malfunction, and the probability importance is more suitable as a basis for judging the reliability of the system.

To improve the reliability of the cold chain system, this paper constructs an optimization model with the object of minimizing the reliability cost and the constraint conditions of the expected system reliability, and proposes an improved reliability allocation model, based on probability importance, which costs less than the primary method based on the feasibility.

Due to the limited data, part of the data in this paper is obtained through a fuzzy comprehensive evaluation. With the development of the Internet of Things, real-time monitoring and control of the entire distribution process environment can be carried out. The follow-up work can study the reliability of the cold chain distribution system based on the collection of historical data. The research can be further improved by establishing the optimization model through converting the feasibility into the actual reliability cost coefficients to reduce the delay of the cold chain distribution and the loss in the circulation process, as well as to improve the distribution efficiency.

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Appendix A

Table A1. Conditional probability table for node B_1.

C_1		0		1
C_2	0	1	0	1
0	1	0.35	0.65	0.23
1	0	0.65	0.35	0.77

Table A2. Conditional probability table for node B_2.

C_3			0				1	
C_4		0		1		0		1
C_5	0	1	0	1	0	1	0	1
0	1	0.63	0.6	0.38	0.3	0.18	0.2	0
1	0	0.37	0.4	0.62	0.7	0.82	0.8	1

Table A3. Conditional probability table for node B_3.

C_6			**0**				**1**	
C_7		**0**		**1**		**0**		**1**
C_8	0	1	0	1	0	1	0	1
0	1	0.39	0.35	0	0.45	0	0.15	0
1	0	0.61	0.65	1	0.55	1	0.85	1

Table A4. Conditional probability table for node B_4.

C_{12}	0		1	
C_{13}	0	1	0	1
0	1	0	0.55	0
1	0	1	0.45	1

Table A5. Conditional probability table for node B_5.

C_{14}	0				1			
C_{15}	0		1		0		1	
C_{16}	0	1	0	1	0	1	0	1
0	1	0.46	0.5	0.23	0.3	0.13	0.15	0
1	0	0.54	0.5	0.77	0.7	0.87	0.85	1

Table A6. Conditional probability table for node B_7.

C_{21}	0				1			
C_{22}	0		1		0		1	
C_{23}	0	1	0	1	0	1	0	1
0	1	0.5	0.1	0.05	0.32	0.16	0.032	0
1	0	0.5	0.9	0.95	0.68	0.84	0.968	1

Table A7. Conditional probability table for node B_6.

C_{17}	0								1							
C_{18}	0				1				0				1			
C_{19}	0		1		0		1		0		1		0		1	
C_{20}	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
0	1	0.8	0.35	0.28	1	0.8	0.35	0.28	1	0.8	0.35	0.28	0	0.42	0	0
1	0	0.2	0.65	0.72	0	0.2	0.65	0.72	0	0.2	0.65	0.72	1	0.58	1	1

Table A8. Conditional probability table for node A_1.

B_1	0				1			
B_2	0		1		0		1	
B_3	0	1	0	1	0	1	0	1
0	1	0	0	0	0	0	0	0
1	0	1	1	1	1	1	1	1

Table A9. Conditional probability table for node A_2.

C_9	0				1			
C_{10}	0		1		0		1	
C_{11}	0	1	0	1	0	1	0	1
0	1	1	1	0	0	0	0	0
1	0	0	0	1	1	1	1	1

Table A10. Conditional probability table for node A_3.

B_4	0								1							
B_5	0				1				0				1			
B_6	0		1		0		1		0		1		0		1	
B_7	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table A11. Conditional probability table for node T.

A_1	0				1			
A_2	0		1		0		1	
A_3	0	1	0	1	0	1	0	1
0	0	1	0	0	0	0	0	0
1	1	0	1	1	1	1	1	1

Appendix B

Table A12. Feasibility influencing factors weight rating table.

	S_1	S_2	S_3
S_1	1	1	1/3
S_2	1	1	1/2
S_3	3	2	1

Table A13. Score table of feasibility influencing factors of each node.

Node	Node Name	The Reliability Symbol of Each Node	Standardization Level	The Difficulty of Fault Detection	Maintainability
C_1	Replenishment delay	R1	7	3	5
C_2	Insufficient warehouse space	R2	2	1	9
C_3	Inadequate transport vehicle	R3	4	2	8
C_4	Inadequate delivery staff	R4	3	3	6
C_5	Improper route planning	R5	9	9	5
C_9	Information system error	R6	5	7	6
C_{10}	Mistaken sorting process	R7	3	6	4
C_{11}	Mistaken EX-warehouse audit	R8	4	7	2
C_{12}	Improper pre-cooling operation	R9	5	6	3
C_{13}	Pre-cooling equipment malfunction	R10	6	3	6
C_{14}	Poor packaging material	R11	3	5	3
C_{15}	Improper handling of loading and unloading	R12	2	4	3
C_{16}	Crush damage	R13	4	2	5
C_{17}	Cold storage power failure	R14	8	4	6
C_{18}	Cold storage standby power failure	R15	7	5	3
C_{19}	Cold storage cooling equipment failure	R16	8	7	5
C_{20}	Cold storage monitoring system failure	R17	7	5	3
C_{21}	Improper driver operation	R18	4	8	2
C_{22}	Vehicle cooling system failure	R19	6	7	5
C_{23}	Vehicle monitoring system failure	R20	8	5	3

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