Ecological Resilience Assessment Model for Airport Cargo Terminals

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Abstract: This paper introduces a framework for assessing ecological resilience in airport cargo terminals, which are vital nodes in the air cargo logistics chain. These terminals encounter both external and internal disruptions, such as natural disasters, economic fluctuations, and public health crises. These challenges necessitate the enhancement of terminal resilience to ensure stable, efficient operations. The concept of ecological resilience, borrowed from ecosystem theory, is applied to assess the ability of airport cargo terminals to withstand and recover from disruptions. This research proposes a comprehensive framework that evaluates resilience across multiple dimensions: preparedness, resistance, recovery, and adaptability. A Bayesian network model is employed to quantitatively assess the ecological resilience of a selected airport cargo terminal. Through empirical analysis and sensitivity testing, key factors influencing resilience, such as personnel management and operational recovery, are identified. The results highlight the significant impact of preparedness and management on improving terminal resilience. This framework provides a valuable tool for airport managers to make informed decisions, ultimately enhancing the long-term stability and competitiveness of the air cargo industry.

Keywords: Ecological Resilience; Airport Cargo Terminal; Resilience Assessment Framework; Bayesian Network; Logistics; Preparedness; Recovery; Adaptability; Operational Resilience

1. Introduction

Airport cargo terminals, as complex logistics systems, are not only crucial nodes in air cargo transportation but also serve multifaceted functions including economic, social, and environmental roles[1]. These terminals play a significant role in both consolidating and transporting goods, acting as key hubs connecting air logistics with ground distribution. The operational efficiency and reliability of airport cargo terminals directly impact the stability of the entire air logistics chain[2]. However, in the face of a dynamic and unpredictable external environment, airport cargo terminals often encounter a variety of sudden risks, such as natural disasters, economic fluctuations, and public health emergencies[3]. Enhancing the emergency response capabilities and ensuring the long-term operational stability and safety of airport cargo terminals have thus become urgent issues in the air cargo industry.

In this context, ecological resilience has become a central concept for ensuring the sustainable development of airport cargo terminals.[4]. Ecological resilience refers to a system's ability to maintain its functions or rapidly restore its functionality in the face of internal or external shocks. In the air cargo industry[5], ecological resilience encompasses not only the physical infrastructure and emergency response capabilities but also the adaptability and coordination of management systems and information systems[6-8].

Existing research on airport cargo terminal management primarily focuses on infrastructure construction, transportation efficiency, and cost control[9,10], with relatively less attention given to the quantification and assessment of the concept of "ecological resilience." Some scholars have proposed resilience assessment models based on ecological systems theory, but these models are often limited to the study of natural environments or individual facilities and have yet to form a comprehensive assessment framework suitable for complex airport cargo terminal systems. This research aims to develop an ecological resilience assessment framework for airport cargo terminals, providing actionable resilience management tools for decision-makers. By quantitatively evaluating the ecological resilience of airport cargo terminals, this study seeks to provide scientific decision-making support for airport managers, enhancing their ability to respond to emergencies and improving the overall competitiveness of the industry.

2. Indicator System Construction

2.1 Concept and Characteristics of Ecological Resilience

Ecological resilience, introduced from ecosystem theory[11], refers to a system's ability to maintain stability or quickly return to its original state in the face of external disturbances or internal changes[5]. As research progresses, ecological resilience has been applied to various complex systems, particularly in modern transportation and logistics.[12-15], gaining widespread attention in the field of modern transportation and logistics[16,17]. In logistics systems, ecological resilience is defined as the comprehensive ability of a transportation system to respond to external shocks and internal changes[18]. In particular, in the air cargo industry, ecological resilience emphasizes the system’s adaptability, recoverability, and long-term operational stability when confronted with uncertainty, risks, and emergencies. It is not confined to the physical infrastructure's risk resistance ability but also includes flexibility in information systems, the adaptability of management systems, and several other aspects.

Current ecological resilience research primarily focuses on two core features: adaptability and recoverability. Adaptability refers to a system's ability to adjust its structure and functions to restore balance after external shocks. It emphasizes flexibility and adjustment capabilities when the system faces environmental changes, ensuring the system operates effectively over time. Recoverability, on the other hand, pertains to a system's ability to return to its original state after an external shock, focusing more on the speed of response and recovery, highlighting the system's recovery capacity and efficiency. These two resilience perspectives - adaptability and recoverability - are complementary in the context of airport cargo terminal research. Adaptability ensures long-term development, while recoverability ensures that the system can quickly resume its functions in the event of a sudden shock.

2.2 Multidimensional Characteristics of Ecological Resilience in Airport Cargo Terminals

Airport cargo terminals, as complex transportation and logistics systems, exhibit ecological resilience not only through the risk resistance of physical facilities but also across multiple dimensions, such as information systems, management systems, and operational models. Due to the specific characteristics of airport cargo terminals, ecological resilience can be analyzed from four dimensions: the system’s multi-level complexity, the variability of the external environment, the flexibility and adaptability of information systems, and the response capacity of human factors and organizational management.

Airport cargo terminals are composed of several subsystems, including cargo handling facilities, information technology, logistics management, and personnel arrangements. Each subsystem faces different risks and challenges, and the interrelationships and coordination between these subsystems determine the overall system's stability. In assessing the ecological resilience of airport cargo terminals, it is crucial to consider the interdependence and synergy of these subsystems, rather than isolating each aspect for evaluation. The operations of airport cargo terminals are significantly affected by the external environment, which includes economic fluctuations, policy changes, climate change, and market demand volatility. These factors introduce substantial uncertainty, posing risks and challenges to the system. Therefore, airport cargo terminals must not only cope with sudden short-term shocks but also possess the capacity to adapt to long-term environmental changes. This adaptability is particularly important in the context of rapid global economic shifts, as the system must be capable of adjusting to these changes.

Modern airport cargo terminals increasingly rely on information systems to support their operations and management. Information systems enhance cargo handling efficiency, enable real-time monitoring of system performance, and provide decision-making support. However, in emergencies, the ability of information systems to quickly adapt and ensure the smooth flow of information is critical to maintaining system resilience. Flexible and adaptable information systems can help the system recover more swiftly and reduce losses during emergencies. Furthermore, airport cargo terminals are not only technical systems but also complex socio-technical systems. Human factors, such as personnel arrangements, operational procedures, and management structures, play a significant role in the system's resilience. Particularly during critical moments, human decision-making, organizational management's response capability, and inter-departmental cooperation directly influence the speed and efficiency of system recovery. Therefore, when constructing an ecological resilience framework for airport cargo terminals, it is essential to fully account for these human and organizational factors to ensure the system can effectively handle various emergencies.

2.3 Determination of the Evaluation Indicator System

This study selects resilience characteristics as the primary indicators for assessing the ecological resilience of airport cargo terminals. Based on the CNKI (China National Knowledge Infrastructure) literature database, relevant literature published between January 1, 2022, and October 13, 2024, was reviewed. A total of 354 papers were retrieved, focusing on resilience evaluation indicators, evaluation indicator systems, and influencing factors. The most representative resilience evaluation indicators were extracted from the literature. Based on the characteristics of ecological resilience in airport cargo terminals, these extracted evaluation indicators were categorized and integrated.

To ensure that these indicators were closely related to the ecological resilience of airport cargo terminals, a series of interviews were conducted with experts from airports, air cargo companies, airlines, freight forwarding companies, and academic institutions. Through these in-depth discussions, closely related indicators were selected and systematically categorized under the corresponding resilience characteristics. This formed a structured evaluation indicator system for the ecological resilience of airport cargo terminals, as shown in Table 1.

Table 1. Ecological Resilience Evaluation Indicator System for Airport Cargo Terminals

First-level Node	Second-level Node	Third-level Node
Airport Cargo Terminal Ecological Resilience (ACTER)	Preparedness(P)	Preparedness(P1)
		Equipment Maintenance(P2)
		Environmental Management(P3)
		Technical Stability(P4)
	Resistance(R)	Emergency Management Ability(R1)
		Emergency Resource Allocation Ability(R2)
		Personnel Safety Assurance(R3)
		Infrastructure Resistance Ability(R4)
	Recovery(Y)	Logistics Service Continuity(Y1)
		Operation area recovery(Y2)
	Adaptability(A)	Training and Education Level(A1)
		Optimized Resource Allocation Ability(A2)
		Intelligent System Level(A3)
		Continuous Improvement and Feedback Mechanism(A4)

3. Model Construction and Empirical Analysis

3.1 Bayesian Network Model

The Bayesian network, also known as a Bayesian belief network, is a modeling tool based on probability theory and graph theory. It is widely used to express and infer uncertain knowledge. The Bayesian network can effectively assess and predict the probability of events, particularly in complex systems where uncertainty is high[19]. For the ecological resilience assessment of airport cargo terminals, the use of Bayesian networks provides a quantifiable and actionable means of evaluation.

A Bayesian network consists of nodes and directed edges, where each node represents a variable in the system (e.g., system preparedness, resistance, recovery, and adaptability), and the directed edges represent dependencies between these variables. The network structure is used to calculate conditional probability tables for each node, which allows for inference and learning. In this study, based on the previously described evaluation indicator system, the researchers constructed a Bayesian network model using GeNIe software. This model can be used to effectively evaluate the ecological resilience of airport cargo terminals and provide recommendations for further optimization, as shown in Figure 1. Through this model, quantitative assessments of the ecological resilience of airport cargo terminals are made possible, offering valuable insights for enhancing resilience management.

The structure of a Bayesian network consists of nodes and directed edges, where each node represents a variable within the system (e.g., system preparedness, resistance, recovery, adaptability, etc.), and the directed edges represent the dependencies between these variables. This can be denoted as $V = \{V_1, V_2, V_3, \dots, V_n\}$ represents the finite set of variables, and $L = \{V_iV_j, V_i, V_j, \in V\}$ represents the set of directed edges.

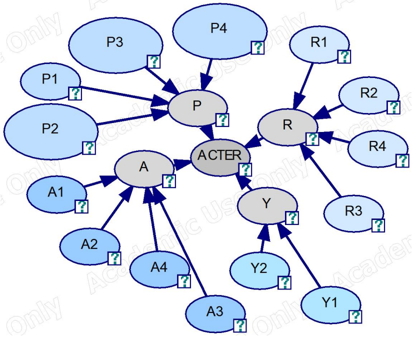

Figure 1. Bayesian Network Model for Ecological Resilience Assessment of Airport Cargo Terminal

Bayesian networks enable reasoning and learning by calculating the conditional probability tables (CPTs) for each node. Specifically, the parameters of a Bayesian network include the prior probabilities for the root nodes and the conditional probabilities for non-root nodes. The prior probabilities are typically derived from historical data or expert knowledge, while the conditional probabilities reflect the probability distribution of a node given the known conditions of its parent nodes. This is commonly represented as $P(A|B) = \frac{P(AB)}{P(B)}$.

3.2 Empirical Study

To validate the effectiveness of the Bayesian network model, this study conducted an empirical analysis, using the airport cargo terminal in Region A as a case study. Region A is a mid-sized cargo hub that faces several challenges regarding ecological resilience. The research involved forming an evaluation team consisting of 11 senior safety management personnel and 15 management personnel from other functional departments in Region A. The team was tasked with evaluating the ecological resilience of the airport cargo terminal.

The evaluation process began by using a fuzzy comprehensive evaluation method to score various evaluation indicators. These scores were then converted into prior probabilities for the root nodes in the Bayesian network. To simplify the calculations and address the complexity arising from a large number of nodes, the study introduced the Leaky Noisy-OR model (LNO), which effectively handles uncertainty and reduces computational load.

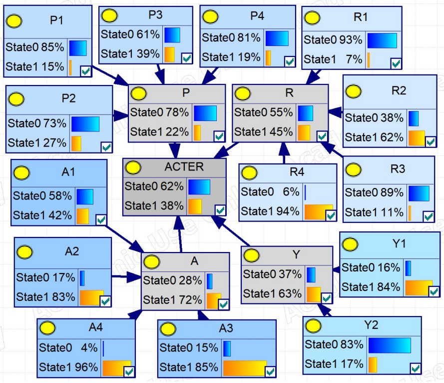

Figure 2. Ecological Resilience Assessment Model of the Airport Cargo Terminal in Region A

As shown in Figure 2, by inputting the prior probabilities and conditional probability tables of each node, the Bayesian network computed the initial resilience level of the airport cargo terminal in Region A. The results showed that under standard operating conditions, the ecological resilience of the airport cargo terminal in Region A had a probability of 38%, with the "unachieved" probability for preparedness as high as 78%.

This finding indicates that although the terminal had some ecological resilience, there was still significant room for improvement.

Further analysis reveals that, in the evaluation model, the achievement probabilities of the sub-nodes under the primary node (ACTER) (preparedness (P), resistance (R), recovery (Y), and adaptability (A)) have a significant impact on the ecological resilience of the terminal,as shown in Table 2. Specifically, when the initial achievement probabilities of these sub-nodes are 0%, the resilience achievement probability of the airport cargo terminal is only 3%. As the achievement probabilities for each dimension increase, the posterior probability of the terminal's ecological resilience significantly improves. Ultimately, when the achievement probability for all dimensions reaches 100%, the resilience achievement probability reaches 95%. The results show that as the achievement probability of each critical dimension increases, the posterior probability of the ecological resilience of the airport cargo terminal significantly improves, thus validating the Bayesian network model and confirming its accuracy.

Table 2. Evaluation Model Validation Table

P	R	Y	A	Posterior Probability
State0	State0	State0	State0	3%
State1	State0	State0	State0	45%
State1	State1	State0	State0	61%
State1	State1	State1	State0	76%
State1	State1	State1	State1	95%

3.3 Sensitivity Analysis and Scenario Inference

To further refine the evaluation results and explore the impact of various factors on ecological resilience, this study conducted sensitivity analysis on the secondary nodes, identifying the most influential factors. After analyzing the sensitivity of the preparedness node (P), as shown in Figure 3, the results revealed that personnel management (P1) had the greatest impact on preparedness, followed by P1 > P2 > P4 > P3. This indicates that personnel management is the most critical influencing factor within the preparedness dimension. Subsequently, the study analyzed other secondary nodes, such as emergency management ability, operational area recovery, and training and education levels. These factors also had significant impacts on resistance, recovery, and adaptability, as shown in Table 3.

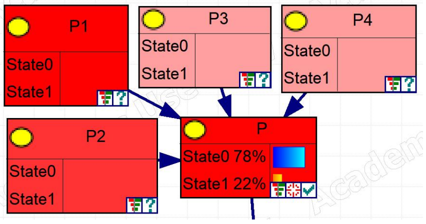

Figure 3. Sensitivity Analysis of the P Node

Based on the results of the sensitivity analysis, the study selected the three highest-sensitivity nodes for scenario inference analysis: P1, Y2, and A1. These nodes represent the most influential factors in preparedness, recovery, and adaptability, respectively. The inference results are presented in Table 4, with Scenario 1 and Scenario 8 representing the extreme cases where all nodes are either unachieved or fully achieved, serving as reference values. Scenarios 2 to 4 describe the changes in ecological resilience when only one node is achieved, while Scenarios 5 to 7 show the changes when two key nodes are achieved. According to the analysis results, personnel management has the greatest impact on improving the ecological resilience of the airport cargo terminal in Region A, particularly in Scenarios 5 to 7, where the simultaneous achievement of personnel management and operational area recovery significantly enhances resilience. Through the analysis of scenario inference, the researchers found that personnel management plays a particularly important role in improving overall resilience. Furthermore, operational area recovery and training education levels are also critical in enhancing recovery and adaptability.

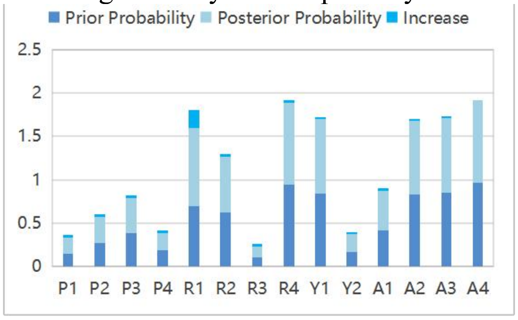

Figure 4. Comparison of Posterior Probabilities before and after Diagnostic Inference of Root Node

To further explore which factors are most crucial for improving the ecological resilience of the airport cargo terminal in Region A, the study also performed diagnostic reasoning analysis,as shown in Figure 4. After setting the probability of achieving the first-level node (ACTER) to 100%, the posterior probability changes of the root nodes were analyzed. The probability of achieving the P node increased from 22% to 44%, a 22% increase. The probability of achieving the R node increased from 45% to 57%, a 12% increase. The probability of achieving the Y node increased from 63% to 78%, a 15% increase, and the probability of achieving the A node increased from 72% to 79%, a 7% increase. Enhancing personnel management and equipment maintenance significantly improves the ecological resilience of the airport cargo terminal in Region A, particularly by improving preparedness (personnel management) and recovery (operational area recovery). These two key dimensions are crucial for enhancing overall resilience. Further analysis showed that when the probability of achieving the first-level node (ACTER) is set to 100%, the changes in posterior probabilities of the root nodes follow a clear pattern. In particular, when resilience is fully achieved, preparedness (personnel management and equipment maintenance) has the greatest influence on ecological resilience, providing clear direction for future resilience development. In addition, emergency management ability, operational area recovery, and training education levels are also factors that require significant attention.

Moreover, the study utilized the reasoning function of the Bayesian network to identify the nodes with the largest posterior probability changes at each level and constructed the optimal improvement path for resilience enhancement by connecting these nodes. The selected optimal improvement path is: "Personnel Management Ability → Reliability → Cargo Terminal Ecological Resilience." This suggests that enhancing personnel management and equipment maintenance is the key path to improving ecological resilience, while also addressing improvements in other dimensions, such as recovery and adaptability.

In summary, the changes in ecological resilience of the airport cargo terminal in Region A are influenced to varying degrees by different nodes, and the contribution of each parent node to its child nodes differs. Through diagnostic reasoning, the study clarified the priority and improvement intensity of each factor, providing strong support for achieving the desired resilience goals. Therefore, future resilience development should prioritize enhancing preparedness capabilities, particularly personnel management abilities, while also improving recovery and adaptability. The optimal path for future efforts is "Personnel Management Ability→Reliability→ Cargo Terminal Ecological Resilience."

Table 3. Sensitivity Values of Secondary Nodes

Rank	Node	Sensitivity	Node	Sensitivity	Node	Sensitivity	Node	Sensitivity
1	P1	0.352442	R1	0.220647	Y2	0.346935	A1	0.27171
2	P2	0.193653	R3	0.148963	Y1	0.256291	A3	0.265317
3	P4	0.0759531	R2	0.135945			A2	0.206721
4	P1	0.073693	R4	0.185345			A4	0.223408

Table 4. Posterior Probability Table from Causal Inference

Scenario	P1	Y2	A1	Reliability	Recovery	Adaptability	Expected Resilience
1	State0	State0	State0	17%	57%	61%	34%
2	State0	State0	State1	17%	57%	88%	37%
3	State0	State1	State0	17%	92%	61%	40%
4	State1	State0	State0	52%	57%	61%	44%
5	State0	State1	State1	17%	92%	88%	45%
6	State1	State0	State1	52%	57%	88%	47%
7	State1	State1	State0	52%	92%	61%	50%
8	State1	State1	State1	52%	92%	88%	54%

3.4 Summary and Recommendations

This study identifies the key pathways for enhancing the ecological resilience of the airport cargo terminal in Region A through the analysis of the Bayesian network model. The research highlights that prioritizing improvements in preparedness, especially factors such as personnel management and equipment maintenance, can significantly enhance the resilience of the entire system. Furthermore, emergency management ability, operational area recovery, and training and education levels are also critical factors that should not be overlooked. Based on the inference results from the Bayesian network, the optimal improvement path is: enhancing "personnel management→reliability→cargo terminal ecological resilience." Therefore, in future resilience building efforts, it is essential to focus on these factors and adjust them flexibly in practical applications to improve the emergency response capabilities and long-term stability of airport cargo terminals.

4. Conclusion and Recommendations

4.1 Conclusion

This study develops an ecological resilience assessment framework for airport cargo terminals, exploring ways to enhance both emergency response capabilities and long-term sustainability. Based on a comprehensive review of existing research, and considering the operational environment of airport cargo terminals, this paper proposes a resilience-focused evaluation framework. The framework's practical applicability and effectiveness are validated through case studies and empirical data. By analyzing the primary influencing factors in depth, the study concludes with the following key findings:

(1) Importance of Ecological Resilience in Airport Cargo Terminals.The research clarifies the crucial role of ecological resilience in airport cargo terminals. As complex systems, airport cargo terminals are influenced by a variety of factors, including ecological environment, logistics flow, technical infrastructure, and management systems. The proposed ecological resilience framework helps to integrate these factors and assess them comprehensively. This, in turn, optimizes cargo handling processes, enhances operational efficiency, and strengthens the system's recovery capabilities in the face of emergencies.

(2) Practical Use of the Evaluation Framework.The evaluation framework developed in this study, which combines both quantitative and qualitative methods, offers a multi-dimensional approach for assessing the ecological resilience of airport cargo terminals. Through case analysis and empirical validation, the framework has proven its feasibility and effectiveness in real-world applications, offering airport managers specific recommendations and decision-making support for enhancing resilience management.

4.2 Limitations and Future Directions

Despite its comprehensive approach, this study has some limitations. First, the framework's scope is relatively narrow, primarily focusing on medium-sized airport cargo terminals. Future research could expand the framework to cover different types of airports, including large international hubs and smaller regional airports. Additionally, due to data limitations, this study did not capture all potential influencing factors. Future studies can enhance the accuracy and applicability of the framework by collecting and analyzing a larger volume of data.

Furthermore, while this study focuses on cargo terminal resilience in terms of preparedness, resistance, recovery, and adaptability, future research could explore the dynamic interactions between these resilience dimensions. Incorporating more complex system dynamics and exploring long-term resilience development could further enhance the model's robustness and predictive power.

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