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Study on Safety Resilience Evaluation of Non-stop Construction in Restricted Area of Large Hub Airport

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Abstract. With the surge of global aviation traffic, the non-stop construction of restricted areas of large hub airports needs to balance facility upgrading and operation continuity. However, the coupling risk of construction and operation double system is prominent, and the existing evaluation has limitations such as insufficient theoretical adaptation and lack of dynamics. Based on the complex system theory and the principle of resilience engineering, this study constructs a three-dimensional evaluation model of "resisting-resilience-learning" and a system containing 27 indicators. The results show that the model can effectively describe the characteristics of resilience. The comprehensive resilience index of Pudong Airport is 0.800, and the optimal resilience and learning force are the main optimization directions. This study fills the gap of the specialized framework for safety resilience evaluation of non-stop construction in the airport exclusion zone, and provides an evaluation tool for similar projects.

Keywords: hub airport, Non-stop construction in the restricted area, Safety and resilience, Principle of toughness engineering

1. Introduction

With the rapid growth of global air traffic, the non-stop construction of restricted areas of large hub airports has become a key measure to balance facility upgrading and operation continuity. However, the coupling characteristics of construction and operation dual-system bring risks such as personnel misoperation and equipment invasion, which pose severe challenges to safety control [1]. As a new paradigm that breaks through the limitations of traditional risk management, safety resilience evaluation builds a whole chain mechanism of risk resistance, function recovery and long-term optimization by quantifying system adaptation, recovery and evolution capabilities, which not only provides support for avoiding major accidents and optimizing resource allocation, but also promotes the transformation of airport management from passive response to active resilience [2].

As shown in Figure 1, at the theoretical level, the theory of safety resilience has evolved from the static perspective of single risk resistance in the early stage to the multi-dimensional dynamic system view covering resistance, resilience, adaptability and transformation force. However, its application in the airport field is still in the embryonic stage, with existing research focusing on operation scenarios such as passenger flow evacuation of terminals and emergency response of air traffic control. The specialized theoretical framework for the non-stop construction of the forbidden

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zone has not been formed, or the ordinary construction model is applied to ignore the constraints of air defense, or the construction technology is only optimized without incorporating the operation dynamics. There is an obvious disconnect between theory and practice, and it is urgent to carry out the integrated innovation of scenarios [3].

From the perspective of non-stop construction management research, although the academic community has made progress in BIM progress visualization, process optimization such as night construction window period design, and risk control such as fault tree and event tree, it has significant limitations. It does not pay enough attention to special constraints such as restricted airspace specification and navigation red line, and focuses on the independent control of construction subsystem. Ignoring the coupling risks with flight scheduling, air traffic control instructions and other operation systems, it is difficult to meet the collaborative security requirements of "dual systems" [4].

In the field of safety evaluation methods, although analytic hierarchy process, fuzzy comprehensive evaluation and other tools are mature, they have prominent static defects and are mostly based on fixed node data evaluation, which cannot reflect the dynamic impact of construction progress and operation adjustment [1,5]. Indicators focus on static dimensions such as "risk probability and loss degree", and lack core indicators of resilience such as "recovery time and adaptation efficiency". Some complex algorithms are difficult to obtain airport data and have limited samples, so they are not suitable enough.

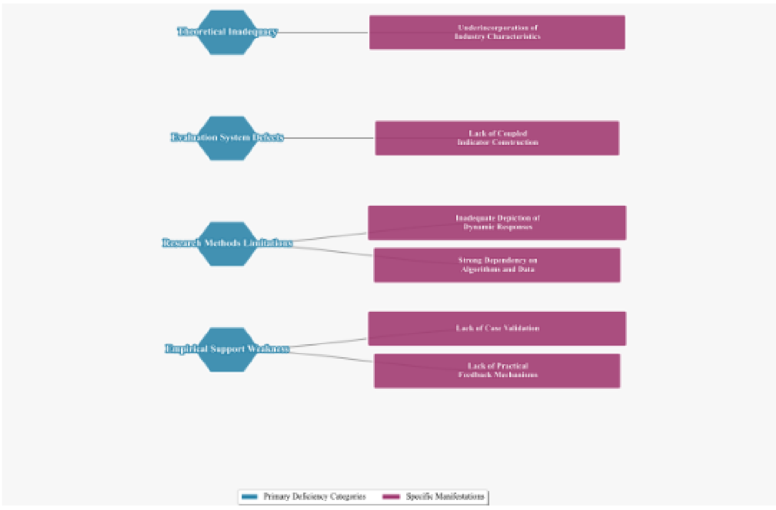

Figure 1. Lack of research

2. Research design

The non-stop construction of the restricted area of large hub airport is a typical dynamic evolution process of complex system, and its safety resilience evaluation needs to break through the limitations of traditional static risk management and build a systematic analysis framework integrating multi-dimensional and multi-scale [6-7]. Based on the complex system theory and the principle of resilience engineering, this paper proposes a three-dimensional evaluation model including resistance, resilience and learning force, aiming to comprehensively describe the dynamic response ability of airport system under construction disturbance. Based on the three-dimensional model framework, this study constructs an evaluation index system including 3 first-level indicators, 9 second-level indicators and 27 third-level indicators.

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In order to solve the problem of ambiguity in the evaluation process, this study develops a combined evaluation method based on cloud model and improved TOPSIS method [8]. The quantitative indicators are converted into qualitative concepts through the forward cloud generator, and the digital features of the cloud model are used to deal with the uncertainty of the measurement data. For qualitative indicators, bidirectional cloud generator is used to realize the conversion between concept and value.

Firstly, the initial decision matrix is constructed, and the dimensional difference between the indicators is processed by the dynamic weighting method. Secondly, the entropy optimization cloud model is used to calculate the degree of each index belonging to the concept of "high resilience". Then the improved TOPSIS method was used to calculate the relative closeness of positive and negative ideal solutions, and the time weight factor was introduced to reflect the toughness change characteristics of different stages of construction. Finally, as shown in Figure 2, Monte Carlo simulation was used for 5000 iterations to evaluate the stability of the evaluation results [9].Among them, random variables were modeled using normal distribution with ±5% fluctuation ranges. Additional perturbation factors were incorporated, including emergency response time variations of ±15% and knowledge conversion efficiency fluctuations of ±20% to account for sensitivity indicators. Weight distributions were simulated using Beta distribution parameters (α=8, β=2) to represent subjective weight uncertainties in the resilience assessment framework.

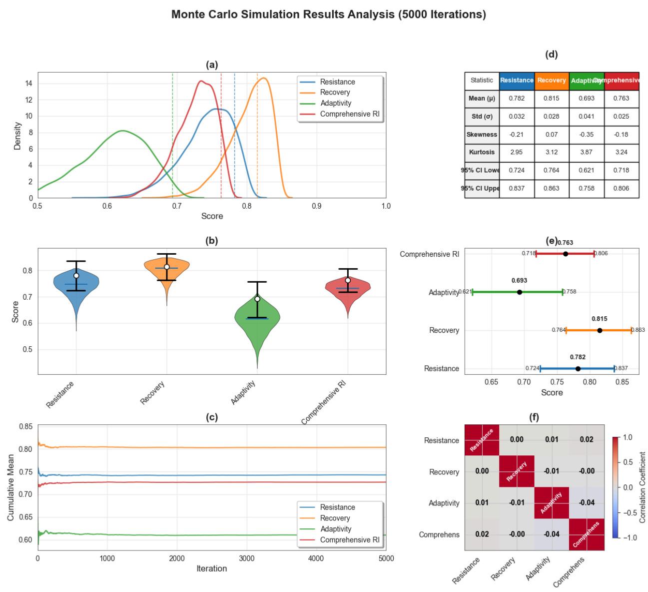

Figure 2. Monte Carlo simulation

Resilience Index (RI) is introduced as a comprehensive evaluation index, and its calculation formula is as follows:

$$RI = \alpha \times \sum (w_i \times C_R i) + \beta \times \sum (w_j \times C_R j) + \gamma \times \sum (w_k \times C_L k) \tag{1}$$

Where $C_R i$, $C_R j$, $C_L k$ represent the cloud membership of the indicators of resistance, resilience and learning, respectively, and α, β and γ are the dimensional adjustment coefficients, and the optimal values are determined by particle swarm optimization algorithm as 0.362, 0.341 and 0.297 respectively.

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The specific evaluation system is shown in Table 1.

Table 1. Evaluation index system

First-Level Indicator(Weight)	Second-Level Indicator(Weight)	Third-Level Indicator	Indicator Attribute	Data Source
Resistance Dimension(0.362)	Physical Protection(0.401)	Hard Isolation Wind Pressure Resistance Level	Quantitative	Measured Data
		Operation Area Buffer Distance	Quantitative	Planning & Design Documents
		Monitoring Coverage Rate	Quantitative	System Logs
	Organizational Preparation(0.327)	Emergency Plan Completeness	Qualitative	Expert Evaluation
		Personnel Qualification Compliance Rate	Quantitative	Personnel Files
		Safety Input Intensity	Quantitative	Financial Data
	Technical Reserve(0.272)	Process Maturity Index	Quantitative	Patent Certification
		Equipment Reliability	Quantitative	O&M Records
		Technical Standard Completeness	Qualitative	Document Review
Recovery Dimension(0.341)	Emergency Response(0.386)	Emergency Activation Time	Quantitative	Drill Records
		Command System Effectiveness	Qualitative	Expert Evaluation
		Information Transmission Accuracy	Quantitative	Communication Records
	Resource Scheduling(0.342)	Standby Resource Activation Time	Quantitative	Drill Measurement
		Cross-Department Collaboration Efficiency	Quantitative	SNA Analysis
		Resource Adaptability	Qualitative	Expert Evaluation
	Function Reconstruction(0.272)	Operation Index Recovery Rate	Quantitative	Operation Data
		System Reconstruction Time	Quantitative	Event Records
		Redundancy Configuration Level	Quantitative	Configuration List
Learning Dimension(0.297)	Knowledge Management(0.356)	Case Library Update Frequency	Quantitative	System Logs
		Experience Feedback Closed-Loop Rate	Quantitative	Audit Reports
		Knowledge Sharing Index	Quantitative	Questionnaire Surveys
	System Improvement(0.332)	Standard Revision Timeliness	Quantitative	Document Audit
		Training System Update Cycle	Quantitative	Training Records
		Defect Rectification Efficiency	Quantitative	O&M System

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	Innovation Application(0.312)	New Technology Application Ratio	Quantitative	Technical Reports
		Process Optimization Contribution	Quantitative	DEA Analysis
		Innovation Achievement Conversion Rate	Quantitative	Achievement Statistics

3. Experimental result

This study selects Shanghai Pudong International Airport as the case study object, and the core lies in its representativeness as the core aviation hub in the Asia-Pacific region [10-11]. Pudong Airport is not only one of the three gateway composite hub airports in China, but also a key hub connecting the world's major aviation nodes. High flight take-off and landing density and complex airline network make the non-stop construction of its restricted area face the typical scenario of "tight construction window period, strong operation constraints and high requirements for multi-subject coordination" [12-13]. In addition, Pudong Airport has accumulated relatively perfect operation data, emergency plans and audit records in the non-stop construction management, which can provide sufficient and reliable data support for the empirical test of safety resilience evaluation model.

As shown in Table 2, the comprehensive resilience index of non-stop construction safety of Pudong Airport Exclusion Zone is 0.800, which is excellent and has a strong overall disturbance response ability. The resilience dimension has the best performance, reflecting that the airport has outstanding ability in emergency response initiation, cross-department resource scheduling and function reconstruction after disturbance, and can quickly restore the operation order. The dimension of resistance is the second, and its physical protection, organizational preparation and technical reserve system are solid, laying a foundation for risk pre-prevention and control. The dimension of learning ability is a weak link, and there is still room for optimization in knowledge management, system improvement and new technology application, which needs targeted improvement to strengthen long-term resilience evolution ability.

Table 2. Comprehensive evaluation results of safety resilience of non-stop construction in Pudong Airport Exclusion Zone

Evaluation Dimension	Dimension Score	Weight	Weighted Score	Grade
Resistance Dimension	0.824	0.362	0.298	Excellent
Recovery Dimension	0.861	0.341	0.294	Outstanding
Learning Dimension	0.702	0.297	0.208	Good
RI	0.800	—	—	Excellent

4. Conclusion

Aiming at the problem of safety resilience evaluation of the coupling of construction and operation systems in the non-stop construction of the prohibited area of large hub airports, based on the theory of complex systems and the principle of resilience engineering, this study constructs a three-dimensional evaluation model of "resistance, resilience and learning", supporting 3 first-level, 9 second-level and 27 third-level index systems, innovating and integrating cloud model and improving TOPSIS method. 5000 Monte Carlo simulations are introduced to ensure the stability of

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the evaluation results, and Pudong Airport is taken as the empirical object to complete the verification.

The empirical results show that the comprehensive resilience index of non-stop construction safety of Pudong Airport Exclusion Zone reaches 0.800, among which the resilience dimension is the best, and the learning dimension is the main optimization direction. At the theoretical level, this study fills the gap in the specialized framework of safety resilience evaluation under the non-stop construction scenario of the airport exclusion zone; At the practical level, the proposed model and method can provide a reusable evaluation tool for similar airports. In the future, the sample can be expanded to cover hub airports of different sizes, the dimension indicators of learning force can be optimized, and the universality of the system can be further improved.

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