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Exploring Schedule Risks in Large Airport Operational Readiness: Risk Identification and the Systematic Model

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Abstract: Large airport operational readiness (LAOR) is a critical factor that directly impacts the opening of airports to the public. However, limited research exists on the risks affecting LAOR schedules. This article explores the risk breakdown structure and risk interactions model of LAOR schedule risk. An empirical investigation was conducted on four large hub airports from 2009 to 2021 using grounded theory procedures. The study identified 21 risk factors categorized into management (highest frequency), technical, process, participant, and environmental risks (lowest frequency), which implied that risks primarily existed within a project rather than in the external environment. A systematic model incorporating risks and their interactions revealed that the primary risk transfer path was from the subject subsystem (participant risk) to the object subsystem (technical and process risk). The findings expand the knowledge domain of infrastructure risk and provide pragmatic risk evaluation and response guidelines. **DOI: 10.1061/JCEMD4.COENG-13697.** © *2023 American Society of Civil Engineers.*

Author keywords: Schedule risk; Operational readiness; Risk identification; Large airport; Grounded theory.

Introduction

Due to general rising income levels, upgrading of consumption patterns, and neighboring cross-regional economic ties (Chen et al. 2011), the scale of air transportation has been growing steadily worldwide. As a result, the air passenger and cargo throughput and airport capacity of many existing airports far exceed their designed service capacity. Hence, there is an urgent need to build or expand large civil airports to provide the expected socioeconomic benefits (Wilke et al. 2014). However, although there is an urgent need to effectively operate large civil airports, schedule management is poor. Large civil airport projects are not immune to scheduling delays (Flyvbjerg 2014). Research on 12 airport projects by the British Airports Authority (BAA) found that none could begin operating on time (Brady and Davies 2010). According to a survey in Indonesia, large airports frequently experience scheduling delays, especially in on-site construction activities (Sitohang et al. 2019). Similar situations also exist in China. Several airports have frequent delays in subsystem work, and airports such as Xiangyang Liuji Airport and Kunming Changshui International Airport have failed to meet their target timelines for opening to operation. These delays resulted in significant economic losses for project owners, operators, contractors, airways, and local governments (Davies et al. 2016). For example, British Airways suffered a loss of $31 million during the first 5 days of the delayed opening of Heathrow Airport T5. The constructors of Blimbingsari Airport lost 14.5% of the contract value due to a 2-month delay (Sitohang et al. 2019). More recently, Berlin Brandenburg Airport began operation almost a decade later than expected, and the final cost was more than €6 billion, three times the forecasted cost (Whyte and Davies 2021). For the operator, the delay of airport operations leads to consumption, including equipment depreciation fees and operational readiness costs, without realizing the expected revenues of airport operations. In addition, because the target operating time of large airports can have strong political significance (Snyder et al. 2019), a delay can result in irreparable reputational damage to a government's transportation department and regional aviation administration (Davies et al. 2016). Furthermore, during the delayed period, social benefits can be lost, which can affect the regional economy with losses that are more significant than project-level losses (Flyvbjerg 2014).

To avoid the consequences of delayed operations, project managers of large airports are required to monitor operational readiness progress closely to determine whether operational requirements are met by the target timeline (Davies et al. 2016). Large airport operational readiness (LAOR) refers to the preparation activities and processes required to ensure normal operations of large airports before they are opened to the public (CAAC 2020a). LAOR involves a tightly coupled technical and organizational system, and its system complexity is reflected in various areas such as projects, technology, stakeholders, and activities (Brady and Davies 2010). First, regarding project characteristics, operational readiness is concerned with many major aspects of operation; large airports are complex systems with multiple subprojects, including passenger terminals, runways, taxiways, aprons, airport internal traffic, municipal engineering, civil aviation, and external supporting engineering, among others. Each subproject consists of a large number of facilities (Davies et al. 2009). Second, the subprojects and facilities require highly professional and technical content for their operation. In addition to conventional building-related operation and maintenance

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(O&M) requirements such as structural, mechanical, and electrical power, the operational conditions of specialized civil aviation systems (e.g., baggage handling, security verification, and flight information display systems) must also be met. Each system contains various subsystems and equipment with complex interfaces and a high degree of integration. Third, in terms of organization, LAOR involves diverse participants, including the owner, operator, consultants, construction-related organizations (e.g., constructors, facility, and material suppliers), operations-related organizations (e.g., airlines, service outsourcers, and merchants stationed in the airport), and relevant government departments (e.g., air traffic management bureaus, customs, and immigration). Finally, complicated LAOR activities are required to integrate facilities, people, and systems in preparation for public opening (Davies et al. 2016). These activities include establishing the operating mode and operations organization, preparing and optimizing the operational scheme, project commissioning and testing, asset handover, and airport operational license application (CAAC 2020a). These operational activities make the airport's "soft" resources and "hard" conditions ready for public opening.

The complexity of LAOR's technical and organizational systems presents significant challenges to schedule management (Vidal et al. 2011; Potts et al. 2021). Various schedule risk factors affect the progress of LAOR, and can jeopardize airport operational target times (Davies et al. 2016). Moreover, due to the interconnectivity between tasks, facilities, and participants, the risks tend to be interrelated, and thus, risk coupling effects are increased (Xue et al. 2020; Yang et al. 2021). However, a proven theoretical model of risk interaction for LAOR does not exist. Therefore, there is a practical and theoretical need to identify the connotation and structure of LAOR schedule risks. Theoretically, the connotation and characteristics of LAOR schedule risks that distinguish them from other risks, and the systematic interactions among risks, should be more deeply understood. In practice, specialized LAOR schedule risk management tools are required for infrastructure project managers with limited prior experience, as a project is usually a one-off case (Davies et al. 2009). Currently, a few studies focus on LAOR schedule risks, and most studies have primarily concentrated on the construction phase (Khalafallah and El-Rayes 2008; Sitohang et al. 2019). While the operational readiness phase schedule risk differs from that of the construction phase—e.g., because the two phases have different management targets, organizations, and required competencies and skills—limited attention has been paid to operational readiness risk (Davies et al. 2009). Hence, a knowledge gap remains in systematically identifying risks affecting LAOR schedules (Snyder et al. 2019). Accordingly, this study aimed to address the following central research questions: (1) what are the LAOR schedule risk factors, categories, and associated definitions? and (2) what are their risk interaction paths, and how can we understand their interactions from a systematic perspective?

To address the above issues, this paper presents a practice-based exploratory study on the schedule risks of LAOR. A long-term tracking investigation of four large hub airports in China between 2009 and 2021 was conducted. The grounded theory approach was used to implement a standard qualitative analysis procedure for risk identification based on the four cases and other project data (e.g., Heathrow Terminal 5 and Hong Kong New Airport projects) used to validate the model. A LAOR schedule risk breakdown structure and a systematic theoretical model of risk interactions were developed. By identifying, analyzing, and progressively developing a foundation framework for managing schedule risk in the operational readiness phase of real-world cases, this study contributes to knowledge in project risk management. The findings of this study can provide direct practical guidance to infrastructure project owners, managers, and operations managers, particularly those involved in airport projects.

Literature Review

Schedule Risk Identification of Infrastructure Projects

Schedule risk identification is a systematic process where specific techniques and tools are used to identify risks that affect schedule (Luu et al. 2009). The identified risks are categorized and structured, with the characteristics of each risk being recorded (Al-Bahar and Crandall 1990). In terms of schedule risk identification techniques and tools, the most common approach is to conduct a literature review and deploy information-gathering techniques such as questionnaires, interviews, brainstorming, the Delphi method, and group review (Gunduz et al. 2015; Siraj and Fayek 2019). Many researchers combine the two approaches to improve identification effectiveness (Nasir et al. 2003; Lo et al. 2006; Choudhry et al. 2014; He et al. 2016; Erol et al. 2020). Case studies have also been employed to identify factors affecting project schedules (Frimpong et al. 2003; Fallahnejad 2013; Biersteker et al. 2021). In construction practice, the risk checklist is a common technique (Lyons and Skitmore 2004). The detailed risk information identified through the aforementioned techniques and tools is always presented in a risk register. A risk register containing complete risk descriptions can serve as a critical tool in the risk identification process (PMI 2013), and it facilitates the formation of a risk knowledge base (Siraj and Fayek 2019).

In terms of schedule risk factors and categories, Assaf and Al-Hejji (2006) identified 73 factors causing delays in large construction projects. They categorized them into groups according to the sources of delay: participants (owner, contractor, consultant, and design team), resources (labor, materials, equipment), project, plan, and environment. Braimah and Ndekugri (2008) identified 18 schedule risks in UK construction projects and employed factor analysis to divide them into six groups, focusing more on the risks generated by schedule management activities. Choudhry et al. (2014) collected seven schedule risk categories of the Pakistani bridge project, including health and financial issues. Their findings indicated that financial shortage is a major risk. Through a systematic review and content analysis of the relevant literature, Siraj and Fayek (2019) classified risks into 11 categories and identified adverse socioeconomic environment as the most common risk. Specific to airport projects, based on a four-level work breakdown structure of airport construction work, Sitohang et al. (2019) identified the top three schedule risks as mismatched construction methods, unavailability of construction materials, and changes in work packages. Khalafallah and El-Rayes (2008) developed a multiobjective optimization model to minimize construction-related security risks of airport expansion projects.

Risk Interactions

Megaproject system complexity leads to risk structure complexity. Its internal and external environments face various risks which, although not independent, are interrelated (Hallowell et al. 2011; Taroun 2014; Williams 2017). In identifying and analyzing schedule risks, more scholars focused on project-level risk interactions and their risk coupling effects (Xue et al. 2020; Yang et al. 2021). In this view, the presence of risk interactions may change the intensity and type of involved risks. Consequently, the level of project risk extends well beyond the linear superposition of individual risk factors, resulting in negative impacts on the project's ability to achieve its objectives, such as maintaining schedule targets (Xue et al. 2020).

Based on the risk identification results, scholars have explored the causal relationships between risks, and between risks and delays. Adopting the classification of schedule risk presented in Assaf and Al-Hejji (2006), Luu et al. (2009) found that adverse factors related to weather, materials, and site handover can directly lead to delays, and that there is a robust causal relationship between the owner- and contractor-related risk factors. Using Bayesian network model simulations, He et al. (2016) found that the risk causal relationship in the management system was a key factor resulting in delays. Furthermore, the interactions between risks from different categories reflect the phenomenon of cross-source risk transfer. Yang and Ou (2008) developed a structural equation model to observe the path coefficient of risk causalities. They found that non-human (environmental) causes are the most important risk categories with high-risk transitivity. Through a social network analysis of tunnel construction projects, Yang et al. (2021) revealed that management risk factors (e.g., ambiguous responsibility assignment and lack of interorganizational coordination) play a critical transmission role in the overall macroscopic risk system of complex projects, leading to project delays.

Key Findings and Research Gap

Schedule risk is a critical and long-term issue in infrastructure projects. Through effective risk identification tools, researchers have identified various types of infrastructure schedule risks, which can be summarized into several groups, such as participant, project characteristics, technology, resources, management, and socioeconomic environment (Nasir et al. 2003; Luu et al. 2009; Mahamid et al. 2012; Choudhry et al. 2014; Gunduz et al. 2015; He et al. 2016; Siraj and Fayek 2019). Despite the different risk perceptions among the parties (Assaf and Al-Hejji 2006), statistically, socioeconomic environment risks, such as unpredictable inflation rates, are the most common risks, followed by technical risks, such as engineering errors, and participant risks, such as unskilled labor (Siraj and Fayek 2019; Mahamid et al. 2012; Choudhry et al. 2014). Moreover, schedule risks interact with each other, which means that individual risks can cause project delays through coupling effects (Luu et al. 2009; Xue et al. 2020). Risk analysis models have revealed that management, environmental, and participant risks tend to display high transitivity in project-level risk interactions (Yang and Ou 2008; Luu et al. 2009; He et al. 2016).

Despite the valuable contributions made in the field of schedule risk identification and interactions, there are still gaps that need to be addressed regarding the research object and methodology. First, the existing risk identification studies predominantly focused on the construction phase. However, due to the different management targets, organizations, required competencies, and skills between the operational readiness phase and the construction phase, findings from the construction phase may not easily apply to operational readiness (Davies et al. 2009). Additionally, studies on airport schedule risk are currently limited to the construction phase, and the conclusion that key risks exist in construction methods and materials is not applicable to the operational readiness phase. Second, previous studies predominantly followed a top-down research paradigm by identifying risks based on literature reviews or expert knowledge and then evaluating risks using quantitative mathematical models. The limitation of this paradigm is its tendency to simplify the research phenomena to build testable research models (Wu et al. 2015). Consequently, it becomes challenging to gain a thorough understanding of factors and mechanisms when exploring complex social and technical phenomena within a specific industry or project (Phelps and Horman 2009), such as the LAOR schedule risk in this study. One way to overcome this constraint is to employ a bottom-up research paradigm that builds theoretical constructs based on extensive and comprehensive analyses of practical projects (Wu et al. 2015). Systematic qualitative methods are particularly well-suited for this approach (Corbin and Strauss 2008).

Methodology

Reason for Using Grounded Theory

Grounded theory is a well-established qualitative method that can be applied to complex phenomena and research fields that have not been extensively studied and theorized (Flick 2018). It requires researchers to investigate real-world phenomena on the ground (Parry 1998) and achieve a bottom-up theory-building process based on sufficient empirical data (Strauss and Corbin 1990). This approach captures and analyzes concepts and logical relationships, and a substantive theory is produced through inductive deduction of the specific phenomenon (Glaser and Strauss 1967). The current study obtained empirical data through an on-site investigation approach to establish a conceptual model of LAOR schedule risk based on a bottom-up research paradigm. Such research goals and settings make this study well-suited to adopt grounded theory.

In recent years, grounded theory has been widely used in construction industry research, primarily to explore the influence factors and mechanisms of sociotechnical management phenomena in the context of emerging high-tech projects (Wu et al. 2015; Liu et al. 2017, 2019; Sithambaram et al. 2021; Burga et al. 2022). Research findings are often presented in a hierarchical framework of influence factors and integrated comprehensive theoretical models. Specifically for risk identification studies, grounded theory has been applied to effectively develop risk breakdown structures and conceptual models of risk interactions (Shojaei and Haeri 2019; Tang et al. 2022). In addition, risk identification is a discovery process that relies on theoretical knowledge, practical experience, and a certain degree of creativity (Chapman and Ward 2003), consistent with grounded theory (Glaser and Strauss 1967). Based on the abovementioned reasons, this study employs grounded theory to identify and analyze LAOR schedule risk.

Overall Research Framework

Following the operational process of grounded theory (Strauss and Corbin 1990), the proposed research steps included collecting and processing original data from four large airports for the three-level coding procedure. The identified factors were integrated using the constant comparative method to obtain a risk breakdown structure, including risk factors, risk categories, and their frequencies. Risk interaction relationships were sorted to construct a basic theoretical model. Secondary data from other cases were used for the theoretical saturation test to ensure that no new risk categories or relationships emerged. Finally, the basic theoretical model was reorganized into a systematic model using systems thinking. High-frequency and high-transitivity key risks were identified, typical cases illustrated the systematic logic of risk interactions, and the corresponding risk migration methods were proposed. Fig. 1 depicts the research framework.

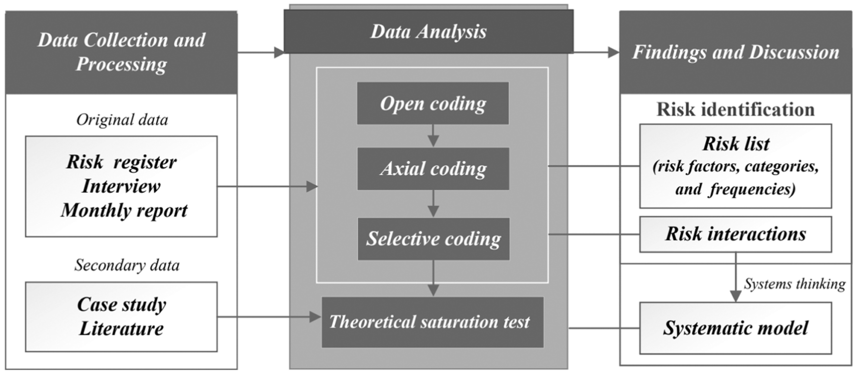

Fig. 1. Research framework.

Data Collection and Processing

Data Collection

Original data were collected from the engineering practices of four airport hubs in China. The project team comprises 31 members, including seven university professors, 18 full-time research assistants, and six Ph.D. students, providing schedule management consulting services to the Civil Aviation Administration of China (CAAC) and the project owner. Between 2009 and 2021, the project team tracked the whole operational readiness process of four airport projects and conducted on-site investigations. The four hubs were Beijing Daxing International Airport, Qingdao Jiaodong International Airport, Shenzhen Bao'an International Airport expansion, and Shanghai Hongqiao International Airport expansion projects. Four airport hubs were chosen as cases to provide original data for the following reasons. First, the four airports are international civil airports whose operations requirements must meet the global unified standards and systems approved by International Air Transport Association (IATA). Their operational readiness follows unified procedures, which include testing, rehearsals, training and handover, etc. Therefore, the selected four cases have domain representativeness (Dul and Hak 2007), and the research findings can be generalized to airports in other institutional contexts. Second, these four airports have reached the standards of super airports as stipulated by the CAAC regarding passenger throughput (CAAC 2020b) and have large operational readiness workloads. As a result, the selected cases comprehensively cover various dimensions of schedule risk. Third, the four airport hubs represent the typical characteristics of LAOR in terms of project scope, technology, stakeholders, and activities (Brady and Davies 2010). Fourth, all four projects faced multiple risks documented by standard risk management processes during operational readiness. As a result, data on their schedule risks were available. Fifth, the locations and ownerships of the selected airports are diverse. Furthermore, all four projects achieved their schedule targets on time or ahead of schedule, primarily relying on effective risk identification and management. The above reasons substantiate the representativeness of the sample and enhance the reliability and generalizability of the findings. In the four projects, the project teams collected project data of LAOR schedule risks from two sources: (1) risk register and (2) key lagging issues. They are summarized below.

1. **Risk Register**. The risk register is the primary output for recording risk information on the four projects. It was obtained through multiple standard qualitative risk identification techniques during three periods (PMI 2017).

During the operational readiness startup period, the project team preset a schedule risk list based on the historical experience of similar projects. Expert assessments of these risks were obtained through facilitated risk workshops attended by senior managers from the airports' departments, as well as risk management experts from government and external entities. The experts verified the preset risk information and amended it according to the specific project scenarios. Brainstorming and scenario analysis were then conducted to complement schedule risks based on the department schedule management plan, professional knowledge, and experience. The initial risk registers, consisting of risk source (department), risk name, risk description, risk owner, and potential risk response, were then collected.

During the operational readiness implementation period, a monthly risk monitoring mechanism was implemented to track changes to the existing risks and identify new risks through semistructured interviews. The interviewees were senior managers who directly participated in the operational readiness, including owners, construction-related organizations, operation-related organizations, and relevant government departments. The interview guide was developed primarily using the items of the risk register, and the interviewees were encouraged to provide in-depth insights into the causes of the identified risks. The interview questions included the following:

a. For new risks:
   (1) Q1. What current risks affect operational readiness progress from the perspective of your department or company?
   (2) Q2. What are the causes of each factor?
   (3) Q3. What are the risk sources, and who are the owners?
   (4) Q4. What are the expected risk response methods?

b. For preexisting risks:
   (1) Q1. Has this risk been reduced currently to an acceptable level?
   (2) Q2. If not, has the risk changed in its content and scope, or has a new challenge emerged?
   (3) Q3. What causes the risk to remain pending?
   (4) Q4. What is the next response method taken to minimize this risk?

The interviews were transcribed into text, and the risk information was added to the initial risk register. A new description of the preexisting risks was integrated into the original one, and the new risk information was recorded following the risk register items.

After the airport was officially opened for operation, the project team comprehensively reviewed and integrated risk information generated during the iterative process discussed above to ensure data integrity. In the final risk register, the relevant elements of risk identification included risk identifier, brief risk name, detailed and structured risk description (including risk cause and effect, if any), risk source (department), risk owner, risk response, and timing information (time of the risk being identified and action taken).

2. **Key Lagging Issues**. Lessons learned from previous projects can form a proven risk identification database for improving future projects' performance (PMI 2017). Therefore, detailed information on key lagging issues was collected as supplementary data. For the four projects, full access was granted to operational readiness-related project documents, including the airport group's monthly reports and weekly meeting minutes, and schedule verification reports from the supervision department in the airport group. Among them, the focus was the issue of lagged critical control time nodes according to schedule plan. Detailed descriptions of the causes and effects of the delays were extracted from the corresponding sections of the project documents. The corresponding transcripts were retained and numbered. The data collection process was completed during the project review phase after the airport officially began operation.

Data Processing

Regarding data types, the risk register was text in an Excel sheet, and information on key lagging issues was raw text. The data were preprocessed to ensure a uniform format. It is necessary to gather specific and well-structured data to fulfill the research aim of exploring the connotation and structure of LAOR schedule risks. The data used for the grounded theory method were risk descriptions recorded in the risk register and detailed descriptions of key lagging issues. Irrelevant information such as timestamps, names of personnel, and departments were removed. The remaining data were arranged in four tables and imported into the NVivo11 software for further refinement. After collation, 723 descriptions were obtained from the four project cases. The 723 descriptions were further filtered to remove poor-quality data, which included (1) descriptions with unclear expressions; (2) descriptions of some issues that are judged to be optimizing items for operational services after the airport's public opening; (3) descriptions of risks judged to exist in the construction phase rather than operational readiness phase; and (4) repeated descriptions of the same risk in an airport project from different respondents. Based on these four categories, 156 descriptions were eliminated, and the remaining 567 descriptions were used as the dataset. At this stage, the dataset met Scott's criteria of authenticity, trustworthiness, representativeness, and meaningfulness for the usability of text data (Scott 1990) to be used for the subsequent coding process.

Further, 567 descriptions were analyzed by members A and B from the project team. Members A and B participated in the entire process of LAOR schedule risk management at Beijing Daxing International Airport and Qingdao Jiaodong International Airport. They have more than 5 years of practical experience and solid theoretical knowledge in the LAOR schedule risk management field. Before the data analysis, 100 descriptions were randomly selected and independently encoded by the two members, followed by a reliability test performed on their coding results. Using the coding comparison function of the NVivo 11 software, the consistency ratios of coding nodes between A and B for the 100 descriptions were all above 80%, which means that the reliability meets the research requirements (Li et al. 2021), and A and B were able to carry out data analysis of the complete dataset. Finally, 300 descriptions were randomly selected from the 567 descriptions for independent data analysis by A, and the remaining 267 descriptions were analyzed by B. This distribution also included the 100 descriptions used in the previous reliability test. Members A and B cross-compared and supplemented the coding results, refining and developing concepts, categories, and theoretical models together to enhance the accuracy and consistency of the research findings.

Data Analysis

Step 1: Open Coding

Open coding is an analytical process that identifies themes and concepts and their dimensions based on an in-depth understanding of objective data (Wu et al. 2015). In the process, the coder reads the collected data sentence by sentence, breaks down the data into several pieces of distinguished valid contents (recorded as a "reference" in the software), and abstracts the reference into concepts (recorded as a "node" in the software) (Liu et al. 2019). This procedure is implemented in the NVivo version 11 Plus software. By examining the dataset, most descriptions contained one reference focused on developing a detailed narrative about a single concept. The concept was named as the original term from data or the summary phrase from the coder (refer to No. 1 in Table 1). In addition, a few passages involving multiple references and causal relationships between different references were found. These were noded as multiple concepts according to the different references (refer to No. 2 and 3 in Table 1), and their causal relationships were recorded in the memos. Through this process, 624 concepts were obtained. An example of the open coding process is shown in Table 1.

The 624 concepts were then integrated by the constant comparative method. For example, taking one concept as an object, other concepts similar or associated by connotation were searched for. In turn, the obtained concepts and their categories were examined against the text, particularly against passages that differ from those that generated them. In this iterative process of induction and deduction, nodes around a phenomenon or core concept were grouped until all of them were applied to each concept category (Osman et al. 2020). In NVivo 11, 624 concepts were grouped into 57 concept categories, and the occurrence frequency of concepts under each category was counted, as shown in Table 2.

Table 1. Example of open coding of raw text materials

Description	Concept
While the risks of individual systems may be easy to control, when systems are integrated, there are integration risks, including not only technical risks but also management risks.	**No. 1** Technical and management issues arising from multisystem integration
The failure of the airport's power supply equipment caused the baggage system to malfunction, affecting the normal sorting of the baggage system.	**No. 2** Power supply **No. 3** Baggage system failure

Table 2. Risk breakdown structure of LAOR schedule risk

Risk category (Main category)	Risk factor (Subcategory)	Risk description (Concept category)	Frequency (f)
Participant risk (f = 105)	Personnel training (f = 34)	Personnel training for owner	15
		Personnel training for external entities	10
		Personnel training for service outsourcers	9
	Operational behavior (f = 32)	Misoperation	13
		Unfamiliarity with the new operating environment	9
		Unfamiliarity with operational issues	10
	Competence and awareness (f = 14)	Insufficient professional competence and experience	11
		Negligence of thought	3
	Job security (f = 25)	Livelihood security for employees	7
		Employee occupational health	3
		Understaffing	15
Technical risk (f = 164)	System complexity (f = 55)	Multisystem integration	11
		Use and maintenance of new equipment and systems	33
		High technology and business volume	11
	System equipment failure (f = 27)	Core system failure	11
		Other equipment system failure	16
	Safety of aviation and operations (f = 68)	Unreasonable design	13
		Incomplete monitoring coverage	5
		Birdstrike prevention	4
		Safety protection of air-traffic control zone	24
		Engineering safety hazards	18
		Information systems security	4
	Supporting infrastructure (f = 14)	Transportation infrastructure	4
		Municipal facilities	10
Management risk (f = 167)	Management scheme (f = 59)	Uncertainty of operations management instruction and scheme	14
		New management scheme	10
		Business or service processes optimization	21
		Inadequate emergency plan	14
	Management mode and organizational structure (f = 32)	Management interface division	20
		Management model changes	7
		Organizational restructuring	5
	Communication (f = 35)	Communication within the owner	7
		Communication between the owner and external entities	28
	Schedule control (f = 41)	Inconsistent work plans	7
		Squeezed operational preparation time due to construction lag	18
		Short time plan or uncertainty of target time	5
		Unclear operational requirements	11
Process risk (f = 154)	Certificate application and approval (f = 18)	Agreement signing and license application	10
		Government approval	8
	Test, trial, and relocation (f = 28)	Insufficient scale of commissioning test	12
		Poor test condition	5
		Inadequate preparation for relocation	11
	Bidding and contract management (f = 35)	Bidding failure or delay	25
		Moral hazard of service outsourcing entities	10
	Guidance and social propaganda (f = 27)	Signs and passenger guidance	20
		Insufficient social propaganda	7
	Asset handover and protection (f = 24)	Handover process complexity	14
		Asset destruction and theft	10
	Commercial operations (f = 22)	Merchant decoration	6
		Investment promotion	12
		Security hazards in merchant operation	4
Environmental risk (f = 34)	Market risk (f = 5)	Immature outsourcing market	5
	Social risk (f = 14)	Epidemic and unrest	6
		Holiday	3
		Policy change	5
	Natural risk (f = 15)	Unfavorable weather	6
		Force majeure	9

Step 2: Axial Coding

The 57 concept categories were independent of each other. Using the constant comparative method, each concept category was evaluated to determine other categories with the same connotation until all the categories were classified. For example, "management interface division," "management model change," and "organizational restructuring" were considered to be related concepts because the organization was the carrier of the management model to take effect, and the interface division was a concrete representation of how the management model was implemented. The three concepts were grouped under the main category of "management mode and organization structure." Finally, the 57 concept categories were summarized into 21 subcategories, and the subordination between them is shown in Table 2.

Following the common schedule risk classifications presented in the literature review, 21 subcategories were classified into five main categories after cluster analysis. These five main categories were referred to as the five risk categories of LAOR schedule risks, which include participant, technical, management, process, and environmental risks. The subcategories were referred to as risk factors in the risk breakdown structure (shown in Table 2).

Step 3: Selective Coding

Selective coding focuses on a core category by generating and integrating axial coding results. The collected evidence validates the connections between the related categories to describe a "storyline" and develop a theoretical model about the core category (Strauss and Corbin 1990).

According to the coding results, the five main categories were at the same level of risk categories that affect the LAOR progress. Schedule risk includes factors that affect the schedule and cause delays (Luu et al. 2009) in which a criterion is applied to identify the core category (Liu et al. 2019). Hence, "LAOR schedule risk" is the core category that governs all the main categories, and is at the top target level of the risk breakdown structure (Table 2). In the context of this study, the "storyline" represents the "risk transmission path" (Brookfield and Boussabaine 2009), which is reflected in the incentive and feedback relationship between risks (Tang et al. 2022). The fundamental theoretical model was constructed by creating storylines based on the causal relationships recorded in the memos during the coding process. As shown in Fig. 2, multiple directional linkages existed between risk categories, and risk transmission was prone to chain effects. Furthermore, a systematic model to analyze LAOR schedule risk was designed to gain insight into these risk interactions.

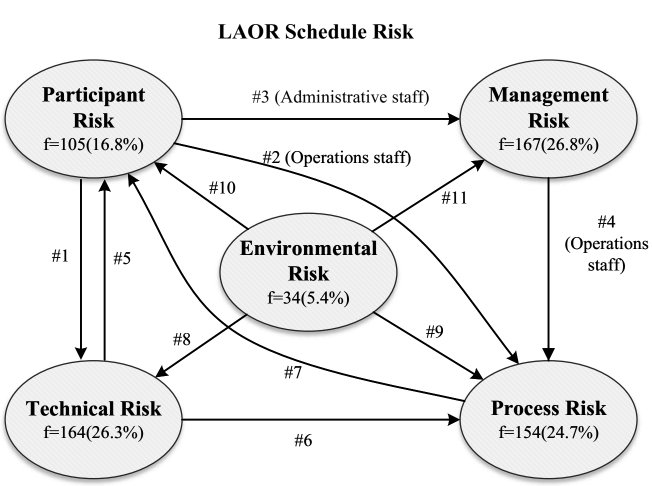

Fig. 2. Basic theoretical model of risk interactions.

Step 4: Theoretical Saturation Test

When new data can neither provide new properties of a certain category nor generate new insights about the theory, it can be inferred that the theoretical model has reached saturation (Bryant and Charmaz 2007). Adopting the idea of "working with various data fragments" (Glaser and Strauss 1967) and Denzin's (1970) "data triangulation" and "investigator triangulation" ideas, data from different cases and different researchers on LAOR schedule risk to perform theoretical saturation tests were selected to ensure that the generated theory can have a high degree of confidence.

In particular, relevant theoretical studies and practical reports for saturation tests (Jia 2009; Li 2011; Shenzhen Airport Group 2014) were collected. Influence factors and difficulties were mined from relevant chapters, and the concepts, corresponding subcategories, and main categories were summarized through the three-level coding procedure. For example, the concepts and categories of organizational management aspects extracted from Jia (2009) on LAOR practices of the Shanghai Pudong International Airport project are shown in Table 3. The analysis of the three works concluded that no risk categories or relationships were found beyond the previous risk breakdown structure and theoretical model.

On the other hand, as the data used for the previous coding were from cases with successful operational readiness, the focus was on typical cases with failed operational readiness—Heathrow Terminal 5 and Hong Kong New Airport project. The schedule risks were identified by reviewing the interviews from international mainstream media, accident reports, and related literature. For example, British Airways claimed that Heathrow Terminal 5 "has problems with the parking system, extended security check time, and the baggage system" (Brady and Davies 2010; Davies et al. 2016). Additionally, staffs were unfamiliar with the new terminal due to the lack of training and essential support. Meanwhile, the terminal's business development manager stated that "the biggest risk is whether there is a large enough load on the baggage system. If any of these things go wrong, the entire system is in trouble immediately (Brady and Davies 2010)." The implicit elements in the above descriptions have the same meaning as the corresponding factors in this study's risk categories of process and participant. After the above two aspects of the theoretical saturation test were examined, it was found that no new concept categories and relationships were generated.

Table 3. Management risk of LAOR in Shanghai Pudong International Airport

Concept	Concept category	Subcategory	Main category
Communication among the branch offices	Communication within the owner	Communication	Management Risk
Communication between the company, airlines and government law enforcement departments	Communication between the owner and external entities	Communication	
Ferry operational scheme	Uncertainty of operational scheme	Management scheme	
Organizational restructuring of branch offices	Organizational restructuring	Management mode and organizational structure	

Therefore, the theoretical model can be considered saturated and used for further discussion.

Findings and Discussion

Identification and Frequency of LAOR Schedule Risk Categories

Management Risk

Management risk refers to factors related to the management tools, organizational issues, and information systems of operational readiness and official operations. Management risk is reflected in the four risk factors described in the practical context of LAOR. The quality and standardization of the O&M scheme determine the core competence of the airport operator (Li 2011), and its specific content depends on the operations management mode and organizational structure. Most of China's large airports have recently adopted an operational mode of "combinations of regional management and professional support (Shenzhen Airport Group 2014)." Therefore, the operations organizational structure was transformed from functional to matrix, which introduced problems of dual leadership and confused management interface. In terms of communication, formal and informal communication between the departments and the owner, and between the owner and external entities, affect the efficiency of vertical and horizontal transfer of information. There are also some LAOR schedule management technique risks—such as the change of work content and compressed duration of following activity due to the workflow logic—contributing to the LAOR schedule management dilemma.

Management risk (f = 167) is the most common risk category from the LAOR practitioners' perspective, indicating that the delays of LAOR are primarily attributed to low management effectiveness rather than other factors, such as adverse environments and technical difficulties. However, an optimistic view is that the management dimension is more prone to human intervention than the target and process dimensions of the project (Marrewijk et al. 2008). This implies that, once the source of risk is accurately identified, management risk can be relatively easy to control later. According to coding results, the most frequent management risk factor is the "management scheme" (f = 59), particularly the business or service processes (e.g., disposal of excess luggage at the departure gate) that need to be optimized. Among the schedule control factors (f = 41), the most frequent one is the "squeezed operational readiness time due to construction lag" (f = 18), such as "construction lags on critical paths may result in insufficient time for pressure testing of various systems." Although the unclear requirement of operating entities (f = 11) (e.g., uncertainty about the terminal operation mode of air traffic control services) is not significant in terms of frequency, this study agrees with Assaf and Al-Hejji (2006) that it is an important source of risk. In addition, "communication between the owner and external entities" (f = 28) has the largest frequency in concept categories. It reflects the characteristics of LAOR, implying that it is jointly oriented by the market and government, and the difficulties lie in the relational governance of multilevel subjects. For instance, "ensuring the operational readiness of the airport public area requires coordination among government departments such as public security, transportation and urban management, as well as relevant service outsourcing entities."

Technical Risk

Technical risk refers to highly technical uncertainties of equipment and systems derived from the functional characteristics of large airport operations. The airport operations systems are composed of multiple subsystems, and the interaction between multiple subsystems adds to the overall nonlinear increase in complexity. When a piece of equipment fails, it can jeopardize a single subsystem or even break down the entire airport operations system. A typical example is "when the airport production platform system experiences exceptional interface issues or network congestion, it can lead to failures in linking the airport's core systems, thereby preventing airport positions from accessing timely production information, resulting in business chaos." Furthermore, safety is the primary consideration of the airport. On the airside and landside, safety threats to people, aircraft, and equipment must be eliminated. Moreover, large airport systems, as the core of urban transportation hubs, need to be integrated with the surrounding transportation systems such as subways, high-speed trains and highways, and municipal resource systems such as energy, water, and networks.

Technical risks (f = 164) have the second highest frequency in the five risk categories, indicating that the high-technology nature of large airports creates significant schedule ambiguity. Most of these risks are intrinsic to the project and cannot be avoided; thus, managers must anticipate and track them. Among the risks, "safety of aviation and operations" (f = 68) is the most frequently observed risk factor. The most frequently observed safety-related issue is "safety protection of air-traffic control zone." This is often attributed to the confusion surrounding access permissions, which can result in unauthorized individuals or items gaining entry into the controlled zone, particularly the airfield, thereby posing a threat to civil aviation safety. System complexity (f = 55) is another high-frequency risk of concern—specifically, when advanced equipment (e.g., self-service check-in and security equipment) or specialized systems (e.g., new baggage handling systems) increase the complexity of a single subsystem, the overall complexity can increase significantly.

Process Risk

Process risk refers to the specific problems in the key tasks of LAOR (Senescu et al. 2013). For instance, before an airport can begin operation, it must complete an extensive process of approvals and permitting, such as acquiring airport operating permits, setting commercial operating procedures, and obtaining airspace approvals. The efficiency of an applicant's preparation and government approval will affect processing progress. Second, the equipment from the previous airport needs to be relocated, while the commissioning test and trial of systems, facilities, operating procedures, and personnel should be conducted. An incomplete relocation plan (e.g., lacking details about the facility location area) may cause a shortage of airport resources, and a lack of comprehensive commissioning tests (e.g., insufficient stress testing in the actual production environment of the system) will introduce uncertainty in operations. Third, there are risks in bidding and contract management. Failed negotiations and contractor defaults can cause delays in the bidding process. Conversely, it is difficult for airport owners to control the moral hazard of service outsourcing entities once the bidding is completed. For instance, "the boarding bridge operators are not responsible for their work. However, they operate independently from the company (owner), and the company bears the risk of equipment malfunction." Fourth, on the landside, inadequate guidance signs will make traffic flow unclear, and in the airside area, insufficient standardization of markings will threaten aviation safety. Moreover, suppose the new airport is not well-publicized on social media before operations begin. Without knowing about the new facility, passengers may go to the previously existing airport, which may generate adverse public opinion of the airport. Fifth, handover is the transition point of the project from construction to operations. The large volume, wide professional fields, and complex functions of transferred entities will affect their delivery progress. Losing assets and equipment due to inadequate protection will also hamper the airport's operations. Sixth, in terms of commercial operations, significant risk factors exist in owners' untimely promotion of the investment, delays in the decoration of merchants, and security hazards for merchants, such as the misuse of high-power electrical appliances during preparation for opening.

Process risk is also a common risk (f = 154), and the frequency of its subordinate risk factors is comparable, representing a more dispersed risk across LAOR critical tasks. The top three risk factors are "bidding and contract management" (f = 35), "test, trial and relocation" (f = 28), and "guidance and social propaganda" (f = 27), which should be given primary attention by managers as described above. Additionally, when multiple projects are tendered simultaneously, procurement needs to be meticulously manged to prevent bidding failure or delay (f = 25). Regarding traffic flow guidance (f = 20), findings suggest the focus should be on whether the signs are standard and functional.

Participant Risk

Participant risk is related to the human resource management of the responsible parties that affect the progress of LAOR. As previously mentioned, human resource factors are at the multimanagement level, multisectoral, and multidisciplinary. To perform the prescribed duties, parties should be equipped with subjective and objective conditions. Lack of professionalism and work efficiency, careless thinking, and irregular operations can jeopardize the competency of any of the parties in their respective roles. In this regard, professional training should be conducted, and members who do not pass the test or receive a certificate should not be permitted to work.

The frequency of participant risk (f = 105) ranks fourth among the five risk categories. This indicates that human factors are not the main reason large airports fail to begin operations on time; this is consistent with the findings of Brady and Davies (2010). However, it contrasts with observations in infrastructure construction, where human resource factors are regarded as a major risk category (Siraj and Fayek 2019). This discrepancy may be attributed to the fact that participants involved in airport operations generally possess professional expertise and have limited staff mobility relative to construction personnel. Among participant risk factors, personnel training (f = 34) has the highest frequency. The difficulties often lie in the wide range of training content, a large number of trainees, insufficient training time, and poor training quality. These difficulties exist with departments of the owner (e.g., practical operations training for personnel in the airfield management department), external entities (e.g., terminal operations-related training of airlines), and service outsourcers (e.g., training of outsourced cleaning staff with complex tasks). Operational behavior (f = 32) is another common factor, as the commissioning and daily operations of the frontline operators are visible representations of their own and the managers' competence, training result, and job security. Misoperation, such as "incorrect commands from the apron controller," and unfamiliarity with the new environment or operational issues, such as "complex aircraft taxiing routes in the apron," can lead to serious safety accidents in official operations, such as "collision of aircraft and vehicle." These issues must be prevented during operational readiness.

Environmental Risk

Environmental risk refers to the threats from the external environment faced by the LAOR management system, which has three aspects: market, social, and natural environment. Market risk refers to the immature market of services and the high cost of some commission services. For instance, "the outsourcing market for boarding bridge operations is immature, and the outsourced price is too high for the owner." Social risks are affected by three aspects. First, epidemics and terrorist activities tend to increase additional airport security services. Second, public holidays and vacation times increase the possibility that employees may not work as scheduled. Third, the operating schedule can be affected by policy changes (e.g., cross-regional government administration issues). Natural risk refers to unfavorable weather and force majeure, such as floods and fires.

As the least frequent risk category (f = 34), the external environment is not a common factor affecting the LAOR schedule from the practitioners' perspective. This is contrary to Siraj and Fayek (2019), who found that the frequency of environmental risks is highest among risks of construction megaprojects. A possible explanation is that, in China's political and social context, large airports are infrastructures with great regional economic and social impact. The central and local governments give political priority and economic support to airport construction, which enhances the ability of the project system to withstand environmental risks. Therefore, practitioners are not sensitive to environmental risks. However, environmental risks are not negligible; on the contrary, environmental risks are difficult to control once they occur. Therefore, the risk evaluation should consider dimensions such as significance and controllability to prevent a black swan event (Chen et al. 2011; Taroun 2014). The identified environmental risks primarily constitute natural risks (f = 15) and social risks (f = 14), and tend to stimulate other risks.

Risk Interactions

Typical descriptions from real-world cases were employed to illustrate the risk interactions more concretely and vividly. The risk relationships are illustrated by the order of serial numbers in Fig. 2.

The participant risk relationships reflect their roles in technical, process, and management risks. Inadequate capacity and misoperation can lead to technical failures, as "the operational errors cause the carousel to stop running," especially in larger scale and more complex equipment and systems, such as baggage, departure, and access control systems (#1). The lack of competence and awareness of operational staff can also cause process difficulties (#2). For example, "the operators lack experience in managing a large terminal. It may lead to unforeseen situations and thus affect the entity handover of terminal equipment and facilities." Another path from participant to process risk passes through management risk as a mediating factor. As administrative staff cannot fulfill their responsibilities, deficiencies in upper-level management systems and organizational vacancies (#3) set traps for process difficulties at the operational level (#4). A typical example is, "due to the lack of seniority and expertise in the operations management department, the airport group does not communicate adequately with external operations users. The operational requirements of users cannot be identified and ultimately leads to the functional defects of the information system developed."

Under the international circumstance that the hardware facilities of large airports are generally upgraded, advanced requirements are put forward for the professional standard and management level of personnel (#5). For example, "the system has more new functions and the operators may not be familiar with the system." Technical complexity also influences the occurrence of process delays (#6). Typically, facility-based tasks are challenged when new equipment is introduced, coupled with system integration issues. For instance, "there are a large number of new devices and systems with complex cross-interfaces in the terminal. It makes asset handover, testing, and commissioning very difficult." In addition, the reaction of the process risk to the participant risk is mainly reflected in the failure to provide the objective conditions for the participants' activities because of the task failure or delay (#7). For example, "the best learning opportunity was missed because the outsourcing of maintenance from the Technical Information Assurance Department was delayed and the maintenance unit could not participate in the commissioning."

Environmental risks dominated by natural and social risks can trigger the four types of risks corresponding to different environmental contexts. Natural risks tend to damage equipment systems (#8) or restrict tasks (#9). For example, "floods back up the terminal's underground corridors and affects the normal operations" and "tractor trailers cannot relocate facilities as planned in low-visibility weather." Social risks, such as national events and administrative systems, tend to disrupt participants (#10) and management systems (#11). For instance, "the Expo has raised higher humane requirements of airport operations, and the training for the airport's resident entities needs to be of higher quality" and "the airport area straddles the Beijing and Hebei regions, the government administration is extremely complicated, and its cross-regional management plan needs to be refined." In addition, an unfavorable environment can reinforce the existing relationships between other risks. For example, evidence shows that "during a severe epidemic, managers have to abandon the traditional site-inspection approach. They have difficulty collecting accurate real-time information and predicting future schedule trends. It may lead to the failure of schedule control tasks." Similar situations can also occur in other risk relationships, resulting in more intense interactions.

Grouping the Risks and Their Interactions into a Systematic Model

The risks and interactions are incorporated into a systematic model to prevent excessive attention to the isolated components while ignoring the critical system characteristics (Loosemore and Cheung 2015). As shown in Fig. 3, LAOR schedule management is a dynamic open system that contains multiple tightly coupled subsystems (Brady and Davies 2010). The risk categories obtained by our coding correspond to the elements of different subsystems. Participant risk corresponds to the subject subsystem of the LAOR schedule management system. Engineering entities, facilities, and task issues at the technology and process risk level constitute the object subsystem. Management risk corresponds to the management subsystem that implements the management functions through mechanisms of incentives, collaboration, and supervision. These three subsystems collectively compose the LAOR project system. The external risks from the natural and socioeconomic environment correspond to the environmental system. The environmental system inputs and exchanges information, materials, and energy to the project system, which changes its state to improve environmental adaptability (Haimes 2006; Jia et al. 2022). When the project system works regularly, under a certain external environment, the subject subsystem realizes the regular operations of material, information, and technical flows in the object subsystem through effective management.

Once a schedule risk occurs in a subsystem, as the risk is transferred within and between subsystems, the risk increases throughout the LAOR schedule management system (Xue et al. 2020). Therefore, the above system operational process also represents the risk transmission path of LAOR schedule risk. According to Haimes (2006), the risk definition of infrastructures is "the integration of inherent vulnerability and the external threat," where vulnerability and threat represent internal and external uncertainty, respectively. The subject, object, and management risk subsystems within the LAOR project system reflect the multidimensional vulnerabilities in personnel, technology, process, and management dimensions. Through paths including business processes, stakeholder

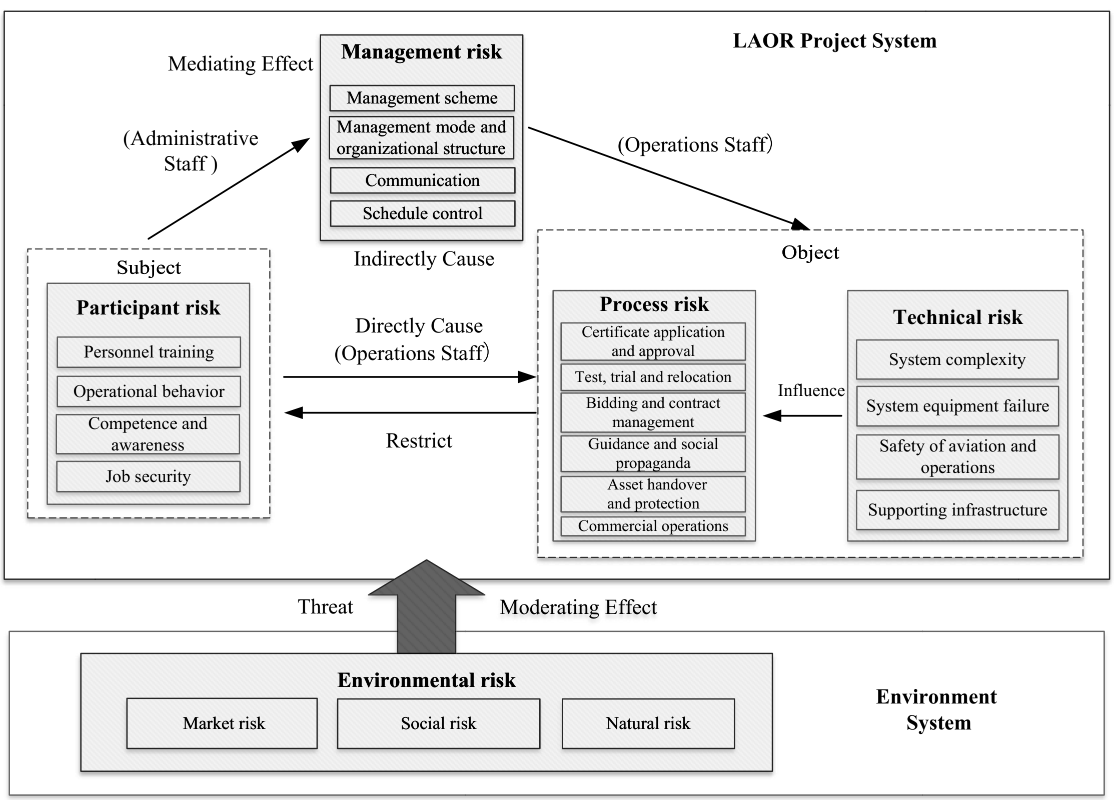

Fig. 3. Systematic model for LAOR schedule risk.

relationships, and the project lifecycle, risks within subsystems continuously increase, risks between subsystems evolve and transfer among each other, and vulnerabilities within the project system increase.

According to the descriptions of risk interactions within the project system, the risk transmission paths between subsystems have a clear directionality. The main risk transmission path is from the subject subsystem to the object subsystem. Direct effects are the effect of participant risk on technical and process risk, and involve frontline operators who directly cause technical failures and process disruptions. Indirect effects are the effect of participant risk on technical and process risks. In contrast, management risks mediate between the subject and object subsystems, where managers and operators are involved. Concurrently, risk in the object subsystem can lead to objective constraints on personnel behavior and cognition, resulting in related risks in the subject subsystem. Moreover, within the object subsystem, the technical complexity of large airports (technical risk) poses difficulties for deploying a series of tasks (process risk) because operations are based on facility systems and their related support.

Furthermore, environmental risks, as an "external threat," exploit the "internal vulnerability" of the project system to disrupt the system from performing a specific function, and increase the risk of the whole system (Haimes 2006; Jia et al. 2022). This implies that, when subsystem risks within a project system enter the threat range of environmental risks, the probability of their occurrence will increase. In addition, environmental risks have a moderating effect on subsystem risk interactions within the project system. When the environment is unfavorable, the normal exchange of resources between subsystems can be blocked; thus, their risk interactions deepen. However, according to empirical evidence, environmental risks in operational readiness are not directly situated within or strongly influence the main risk transmission paths, nor do they have a significant impact on the overall risk level of the project, as observed during the construction phases of infrastructure megaprojects.

Conclusion

In infrastructure megaprojects worldwide, failures and delays in operational readiness have resulted in substantial losses. However, knowledge gaps remain in systematically identifying schedule risks and providing management tools in the operational readiness phase. Based on empirical data from four large hub airports, this study explored LAOR schedule risks and risk interactions through a grounded theory approach and incorporated them into a systematic model. Specifically, a risk breakdown structure was developed containing five risk categories (in decreasing frequency: management, technical, process, participant, and environmental risk), 21 risk factors, and 57 concept categories for detailed risk description. LAOR schedule risks and their interactions were incorporated into a systematic model, where risks were integrated into a project system (including subject, object, and management subsystems) and an environmental system to present the risk flows in a more macroscopic view.

This study contributes to the knowledge area of project risk management in the following aspects. (1) Diverging from the predominant focus on risks in the construction phase, this study focused on schedule risks in the operational readiness phase. This study broadens the understanding of schedule risks in mega-infrastructures by thoroughly examining their sources, structures, and interactions within the context of the transition from one-off projects to permanent routine operations. (2) The findings revealed that LAOR schedule risks primarily originate from and interact within the project system, as opposed to findings in previous infrastructure construction studies, which indicated that the external socioeconomic environment exerts the most influence on construction progress. (3) Existing research on risk identification and risk interactions heavily relied on previous literature and mathematical models. In contrast, this study was rooted in engineering practice and used qualitative methods to identify risks from objective data, which offered specialized and in-depth understanding of LAOR. (4) In contrast to the retrospective examination of failure cases, this study focuses on cases where risk management tools were developed proactively, enabling effective anticipation and control of risks.

The findings of this study provide direct practical implications for owners, project managers, and operations managers of infrastructure projects, particularly airport projects. First, the risk breakdown structure identified in this study serves as a valuable risk management toolkit for practitioners. Second, the insights gained regarding risk prioritization, risk interactions, and the systematic model can guide practitioners in resource allocation decisions. Specifically, the internal vulnerability resulting from the blending of personnel failures, management leaks, and the technical and process complexities of the project affects the progress of LAOR. The study found that, in terms of frequency, management risk is the most common risk category, and the direct and indirect risk transfer paths from the subject subsystem (participant risk) to the object subsystem (technical and process risk) require special attention. If risks can be eliminated at their source, it is advisable to consider enhancing the integration of operational readiness with other phases from an organizational perspective. By incorporating operational readiness considerations into earlier phases of the project lifecycle, such as decision making and construction, potential risks can be proactively identified and addressed. This integration allows for more holistic and coordinated management of risks, enabling project teams to take necessary precautions and implement cross-functional strategies to mitigate potential challenges.

This study provides a starting point for future research on risk management for the operational readiness of mega-infrastructures. However, certain limitations should be acknowledged. First, the main body of data used in this study was derived from four airports in China. Although the four airports met the international standardization for operational readiness of large civil airports, and the findings have been validated by saturation test of cases in other institutional contexts, it is crucial to expand the number, variety, and geographic locations of the cases in future studies. This expansion will enhance global applicability and generalizability of the findings. In addition, due to data constraints, only statistical risk frequency was used in this study as the criterion for management priority. In future studies, there is an opportunity to focus on risk analysis of operational readiness of mega-infrastructures, especially combining quantitative data from various cases with advanced risk analysis methodologies to perform multidimensional risk analyses. Further, it is worth exploring the potential coupling between risks in the operational readiness phase and other phases, such as construction and operations, considering their specific project management modes. Empirical case studies can provide valuable insights into these interdependencies and improve our understanding of how risks propagate and interact throughout the project lifecycle.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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