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REDUCING UNSAFE BEHAVIORS IN AVIATION MAINTENANCE: A STUDY ON FORMATION MECHANISM AND INTERVENTION STRATEGIES BASED ON SYSTEM SIMULATION

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Abstract. Aviation safety problems lead to casualties and property damage, with unsafe behaviors of aviation maintenance personnel being a critical factor. This study firstly constructed a four-stage cognitive model (information acquisition, information processing, response selection, and action execution) to build a cognitive model about unsafe behaviors. In the first two stages, an information processing model was established to analyze personnel cognitions, while in the latter two stages, the Theory of Planned Behavior (TPB) was used to explain operational decision-making. Subsequently, an Agent-Based Modeling (ABM) framework was developed to simulate multiagent interactions in aviation maintenance environments. By synthesizing safety responsibilities across managerial hierarchies, interaction rules between operators and managers were formalized, which was rigorously described by ODD (Overview, Design concepts, Details) protocol to ensure clarity and generalizability. Finally, the ABM was visualized on NetLogo platform and validated through a case study of a maintenance operation. Then simulation analysis of different intervention strategies was conducted to quantify the efficacy in reducing non-compliant operations, providing actionable recommendations. This study innovatively integrated perspectives from social psychology and cognitive psychology to investigate the cognitive model of unsafe behaviors among aviation maintenance personnel. The findings provided a foundational reference for developing safety management strategies in aviation maintenance.

Keywords: aviation maintenance, unsafe behavior, cognitive model, Agent-based model, simulation analysis, safety.

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1. Introduction

Unsafe behaviors of aircraft maintenance personnel cause between 20% and 30% of inflight shutdowns, over 50% of flight delays, and over 50% of flight cancellations in the world (Li et al., 2023). Common risky conducts include improper installation of parts, inadequate inspection/testing/fault isolation, damage to aircraft equipment, and omissions in work. Compared with other industries, noncompliant acts in aircraft maintenance are characterized by collectivity, reversibility, and severe consequences (Tyagi et al., 2023).

Scholars have investigated unsafe behaviors among aircraft maintenance personnel from various perspectives. From a managerial standpoint, understanding the antecedents of safety behaviors is of great importance for safety improvement (Aktas & Kagnicioglu, 2023). Safety culture is recognized as a prominent factor for safety as it influences safety behaviors in the literature (Ni et al., 2023). On the other hand, safety climate, which reflects a temporal aspect of the safety culture at a certain period, has been linked to the safety performance of organizations in many studies (Maneechaeye & Potipiroon, 2022; Mezentseva et al., 2023; Peker et al., 2022). Likewise, research over the last decade indicated that safety leadership influences safety behaviors and safety outcomes (Hong et al., 2023; Yi et al., 2025).

In terms of individual behavior, Jiang et al. (2021) emphasized the importance of management attitudes and group norms in predicting aviation based on the Theory of Planned Behavior (TPB). Chen et al. (2016) constructed an intervention model for unsafe behaviors of maintenance personnel using system dynamics methods, and dynamic simulation tests showed that appropriately increasing special investments in operational environment safety and punishment intensity effectively intervenes in unsafe behaviors of aircraft maintenance personnel. Fogarty and Shaw (2010) found that individual characteristics such as safety attitudes, safety awareness, and safety knowledge all influence the safety conscious practices of civil aviation maintenance personnel. Wang and Hou (2015) studied the impact of various resource management factors on risky operations of maintenance personnel from the perspective of maintenance resource management.

Unsafe human acts are one of the direct causes of accidents (Fu et al., 2017). Reducing and controlling unsafe behaviors by aircraft maintenance personnel and improving human reliability in the maintenance system are important ways to enhance civil aviation safety levels. However, current scholars at home and abroad mostly focus on individual unsafe behaviors of aircraft maintenance personnel, ignoring the issue of unsafe behavior transmission within groups. Human acts and diseases share certain similarities, with both having susceptibility and infectivity (Han et al., 2025; Huang & Cui, 2019; Sun & Tong, 2025). Since aircraft maintenance activities are basically carried out in crew teams, this team-based operation provides conditions for the spread of unsafe behaviors.

However, when controlling unsafe actions of aircraft maintenance personnel, managers often adopt intervention strategies that address symptoms rather than root causes, ignoring the dynamic evolution mechanism behind such behaviors (Aktas & Kagnicioglu, 2023). Therefore, from the perspective of cognitive theory and taking groups of aircraft maintenance personnel as the object of research, this paper used complex system simulation methods to explore the influencing factors and action mechanisms of unsafe behaviors, in order to formulate appropriate intervention strategies and effectively reduce unsafe behaviors of maintenance personnel.

2. Method

2.1. Conceptual model of cognitive mechanism of unsafe behavior

The theoretical foundations for researching unsafe acts include the TPB (Anebagilu et al., 2021), Behavioral Cognitive Theory (Ni et al., 2024), Accident Causation Theory (Guo et al., 2021; Li et al., 2024b), Behavior Based Safety (BBS) Theory (Zhang et al., 2023). These theories explore the internal mechanisms of unsafe behaviors from the perspectives of psychology, behavioral science, or organizational management. Many scholars argue that the cognitive processes underlying unsafe conducts explain their internal mechanisms, positing that unsafe behaviors stem primarily from failures in cognitive processes (Akdeniz et al., 2025; Deng et al., 2022a; Xiao et al., 2023; Zhao et al., 2024). Therefore, personnel cognition has the greatest impact on safety performance. Meanwhile, cognitive models have been widely used by scholars to model unsafe practices of workers in various industries (Wu et al., 2024; Yin et al., 2020). Therefore, this study will adopt a cognitive model to investigate the formation mechanism of unsafe behaviors among aircraft maintenance personnel.

Many studies have divided cognitive processes into multiple stages for research (Jin et al., 2025; Li et al., 2025; Liang et al., 2025; Yang et al., 2024). A general cognitive model applicable to unsafe behaviors of frontline workers was proposed (Deng et al., 2022b), as Figure 1 shows, which includes four stages: information acquisition, information processing, response selection, and action implementation. Therefore, this study adopts a four-stage cognitive model to analyze unsafe behaviors of aircraft maintenance personnel.

Information Acquisition is the first stage, where aircraft maintenance personnel search for potential hazard information in the external environment through experience and knowledge stored in their memory (Fang et al., 2016). Maintenance personnel actively scan their work environment for potential dangers. Those with a strong sense of safety prioritize safety and consciously search for potential hazards during their work. In contrast, those lacking safety awareness trust their memory and experience, failing to check for potential dangers in their tasks. Maintenance personnel proceed to the next stage only if they successfully identify potential hazards.

Once maintenance personnel successfully identify potential hazard information, the cognitive process advances to the second stage: information processing (Huang & Cui, 2019). In this stage, potential hazard information is transformed into problems and subproblems. Maintenance personnel search their memory for relevant experience or knowledge based on the principles of “similarity matching” and “frequency heuristics” to conduct simple judgments and reasoning. The main tasks of this stage include assessing the level of danger and determining appropriate response strategies. Sufficient safety knowledge is critical

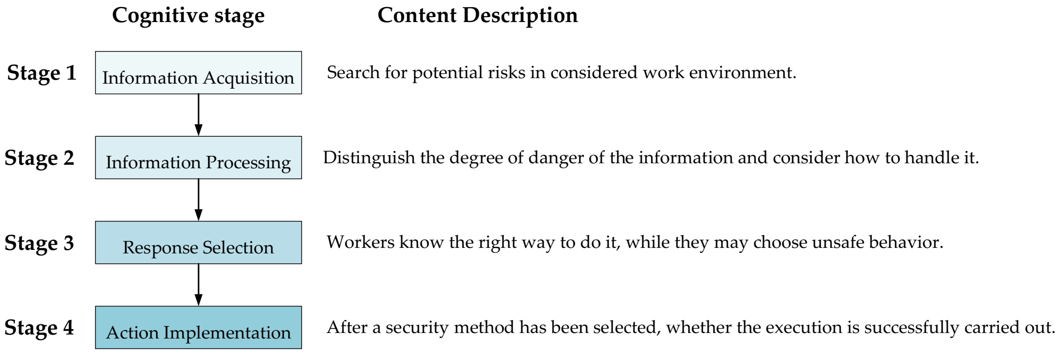

Figure 1. Behavioral cognitive model and content description of each stage

here – if maintenance personnel lack adequate knowledge, they may fail to fully understand risks, underestimate safety hazards, or even ignore potential dangers and directly engage in non-compliant operations.

In the third stage, maintenance personnel already know the correct way to address potential hazards, but whether they finally choose the safe response remains uncertain (Deng et al., 2022b). This is because their decisions are influenced by various factors. For example, they may opt for risky conducts due to reasons such as seeking comfort, desiring peer approval, difficulty accessing safety equipment, or pressure from managers to prioritize efficiency. Notably, since maintenance personnel are aware of the correct response at this stage, their conduct reflects rational.

If maintenance personnel choose unsafe behaviors in the response selection stage, the cognitive process is deemed a failure (Deng et al., 2022a). If they choose safe behaviors, they advance to the action implementation stage, where even successful decisions result in unsafe outcomes due to execution failures. Most failures in this stage stem from individual skill limitations, preventing maintenance personnel from effectively translating intentions into practical actions.

2.2. Multi-agent interaction model for unsafe behaviors of aviation maintenance personnel

This study collected the organizational structure of a certain civil aviation company and screened out the main responsibilities. The managers related to the safety of the front line of aviation maintenance include senior managers, crew leaders, and safety officers. The corresponding safety responsibilities in the main duties of the abovementioned managers are different, and their influences on the maintenance personnel are also different.

This paper will use the "ODD (Overview, Design concepts, Details) Protocol" to describe the model details, which is a general format and standardized structure for describing Agent-Based Modeling (ABM) models. ODD helped to systematically scan the original model description, while NetLogo proved easy and quick to learn, but difficult to debug when implementation problems arose (Grimm et al., 2025). The ODD Protocol has been applied to ABM models in multiple fields such as behavioral science (Racca et al., 2022), social science (Cabuya-Padilla et al., 2025), and epidemiology (Innocenti et al., 2021).

The model contains four types of subjects, namely, maintenance personnel subject, safety officer subject, senior management subject, and onsite management subject (Wu et al., 2010). As Figure 2 shows, except for the main body of maintenance personnel, the other three types of entities correspond to different levels of managers and choose their main work behaviors for interaction, forming a closed loop. Senior managers issue relevant safety guidance and control instructions to middle level managers (safety managers and onsite managers) based on the safety performance of maintenance personnel at the maintenance site; The safety manager receives safety control instructions, interacts with the maintenance personnel through safety training and inspections, and improves the working conditions at the maintenance site; After receiving the safety instructions, the site manager adjusts the behavior feedback and demonstration to reduce the unsafe actions of the maintenance personnel; If senior managers attach great importance to the safety management of maintenance sites, they will participate in some safety activities to demonstrate their level of importance for safety. The above multiparty acts form an interactive closed loop.

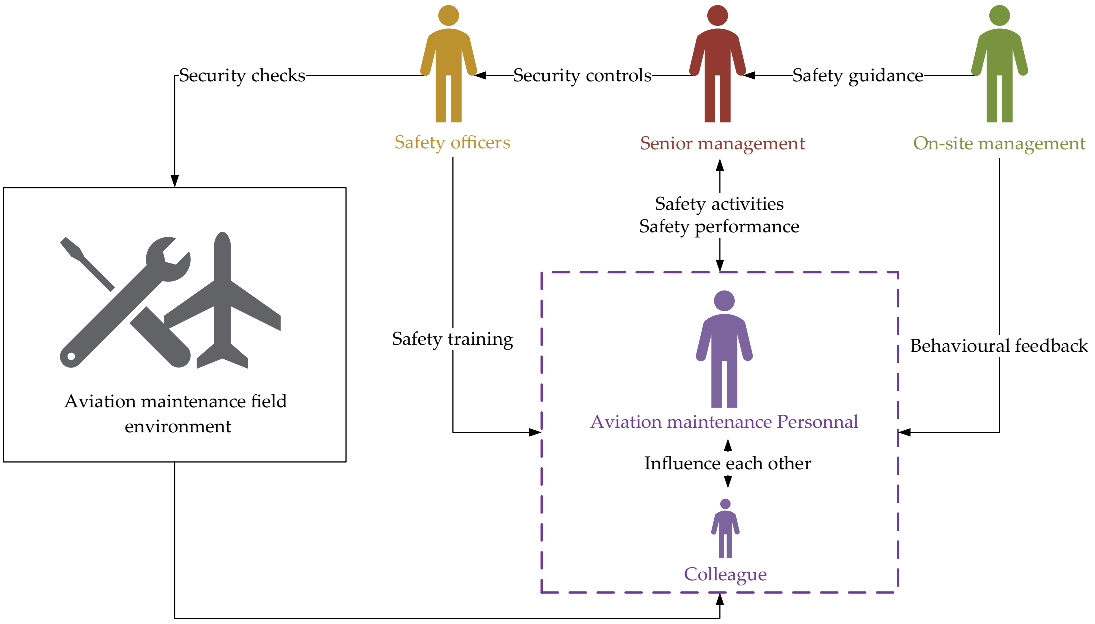

Figure 2. The relationship between maintenance personnel and managers at all levels

2.3. Variables of the agents and their definitions

The maintenance personnel are the origin of the accident cause, and their unsafe behavior is the result of cognitive failure, as well as the final output of the model (Hobbs & Williamson, 2002). Referring to the cognitive conceptual model of maintenance personnel and the multiagent interaction model mentioned earlier, the variables related to unsafe behaviors of maintenance personnel are defined as shown in Table 1.

The interaction between safety officers and maintenance personnel involves safety inspections, safety training, and safety accident statistics (Wachter & Yorio, 2014). In safety inspections, the responsibility of safety officers is to identify and eliminate unsafe physical conditions on site and correct unsafe behaviors of workers. The effectiveness of this depends on the scope of the inspection and the safety officer's safety inspection capabilities. The main variables of safety officers are shown in Table 2.

Table 1. Variables of maintenance personnel and their definitions

Variable	Definition
SAW	Safety awareness of maintenance personnel. 0 means no security awareness, and 1 means security awareness is fully present.
SAT	Safety attitude of maintenance personnel. 0 means a lack of attitude towards safety, and 1 means an excellent attitude towards safety.
SK	Safety knowledge of maintenance personnel. 0 means no security knowledge, and 1 means security knowledge is fully present.
SN	Subjective norms of maintenance personnel. 0 means the external influence is felt poorly, and 1 means the external influence is felt well.
FN	Onsite management norms for maintenance personnel. It means the importance that onsite managers place on site safety.
WN	Worker norms for maintenance personnel. It means the importance that workers place on site safety.
w	Social identity. The degree of recognition of the project. 0 means no impact, and 1 means full approval.
P	Risk understanding factor. Greater than 1 indicates overestimation, and less than 1 indicates underestimation.
PBC	Behavioral control perception. 0 means no control behavior is perceived, and 1 means control behavior is completely perceived.
FR	Whether potential risk information is found. It is a binary variable, 1 is discovered, 0 is not discovered.
CB	Whether unsafe behavior is chosen. Binary variables, 1 is a choice, 0 is not a choice.
FA	Fatigue degree. 0 means no fatigue, 1 means very tired.
UB	Whether unsafe behavior has been done. Binary variables, 1 means an unsafe behavior, 0 means a safe behavior.
ACC	Whether a safety accident has been caused. Binary variables, 1 means an accident, 0 means an accident has not occurred.
ST_{SA}	Impact of safety training on the safety awareness of maintenance personnel.
ST_{SK}	Impact of safety training on the safety knowledge of maintenance personnel.
ACC_{SAT}	Impact of accidents on the safety attitude of maintenance personnel.
CW_{WN}	Impact of the behavior of other maintenance personnel on the norms of colleagues of maintenance personnel.
RM_{FN}	Impact of onsite management's feedback on the leadership norms of maintenance personnel.
BF_{FN}	Impact of the behavior of the onsite manager on the leadership norms of maintenance personnel.
a_1	Impact coefficient of safety attitude on the risk acceptance of maintenance personnel.
a_2	Impact coefficient of subjective norms on the risk acceptance of maintenance personnel.
a_3	Impact coefficient of action control perception on the risk acceptance of maintenance personnel.

Table 2. Variables of safety officers and their definitions

Variable	Definition
SI	Scope of security checks.
C_{SI}	Strength of security checks. The ability of the safety officer to rectify potential safety hazards in the safety inspection.
SG_{CSI}	Impact of the guidance and control of senior managers on the inspection strength of safety managers.
SG_{SI}	Impact of the guidance and control of senior managers on the scope of the safety manager's inspection.
STR	Frequency of safety training. N indicates that security training is held at an interval of N days.
NA	Number of unsafe behaviors per day.
ACC	Number of accidents per day.

The onsite management includes the unit leaders, whose main behaviors are behavior feedback and role model demonstration (Chen et al., 2020). One is behavioral feedback, such as praising maintenance personnel for safe behavior and correcting and criticizing maintenance personnel for unsafe behavior. Secondly, it serves as a role model and demonstration. When onsite managers and maintenance personnel work together, maintenance personnel will decide their own behavior based on whether their leaders are implementing all safety requirements. The variables of the onsite management are shown in Table 3.

If senior management participates in safety activities, such as safety training, the effectiveness of the activities will be enhanced (Alavosius et al., 2017). Therefore, the model introduces the variable of Senior Management Participation (P_{SM}) to represent the probability of senior management participating in each safety training (Anderson et al., 2021). Senior managers check safety performance every day, and if the safety target SG is exceeded, safety officers and onsite managers will strengthen safety control measures; If the safety target SG is not achieved for three consecutive days, the safety officer and onsite manager will relax, and the safety control measures will gradually weaken.

Each patch in NetLogo has attributes to represent the workplace of the maintenance personnel. In this modelling, it is the apron, as shown in Table 4.

Table 3. Variables of onsite management and their definitions

Variable	Definition
RM	Role model. The probability of unsafe behavior by site managers.
BF	Behavioral feedback. Varies between –1 and 1.
SG_{LE}	The influence of the guidance and control of top managers on the role models of field managers.
SG_{BF}	The impact of the guidance and control of senior management on the behavioral feedback of field managers.

This model simulates the cognitive process of maintenance personnel during work, as well as the interaction between maintenance personnel, colleagues, and managers at all levels, with a daily time step. When the model is initialized, the main tasks include:

1. designing the site distribution of the model based on the maintenance site layout of the project;
2. Create four main entities based on the personnel organizational structure in the project: maintenance personnel, onsite managers, safety officers, and senior managers, and create and store the initial values of variables for each entity;
3. Allocate the activity venues of each subject in the model based on the unit situation and positions in the project, to reflect the process oriented maintenance site.

The interaction rules between workers and others mainly includes: accident consequences, safety training, safety inspections, the influence of fellow workers' behaviors, fellow workers' behavior inspections, feedback and demonstration from onsite managers, guidance and control from senior managers, and participation of senior

Table 4. Variables of site environment and their definitions

Variable	Definition
AR	The actual size of the risk. It means degree of the potential risk in the work task and the distribution level of the potential risk on site, with values ranging from 0 to 1.
ER	The exposure of the risk. It means the possibility that the maintenance personnel in an unsafe state, with a value between 0.0005 and 0.02.
SF	Safety facilities. It refers to the availability of safety equipment and facilities in the work scenario. n% of security facilities are available.
Location	Floor plan. According to the layout of the maintenance site, the site division of the maintenance and the allocation of the working area of the maintenance personnel.

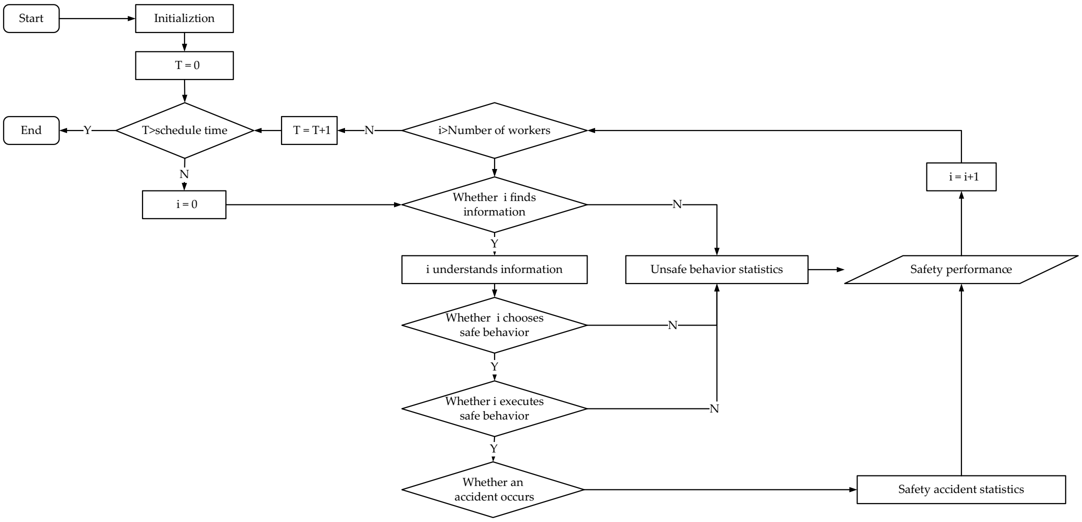

Figure 3. Operation process of the maintenance personnel

managers in safety activities (Wu et al., 2010). The above interaction behaviors depend on whether the corresponding conditions meet the requirements. When the time run reaches the project duration, the model stops running and outputs the required safety performance data for easy statistics. Figure 3 shows the process of the maintenance personnel in the model.

2.4. Behavioral cognitive sub-model for maintenance personnel

The behavioral cognitive sub model of maintenance personnel is divided into four stages: obtaining information, thinking about information, choosing responses, and taking actions. The logical process of its impact on unsafe behavior is shown in Figure 4.

The main cognitive influencing factor for maintenance personnel in the information acquisition stage is safety awareness. Because in maintenance sites, maintenance personnel detect potential safety risks through their sensory organs. The higher the safety awareness, the greater the probability of maintenance personnel discovering potential safety risks (Campolettano et al., 2017). After discovering potential hazardous information, maintenance personnel perceive the risk from the actual safety risk level in the external environment and the information stock in temporary memory and knowledge base (Huang et al., 2019). In the response selection phase, maintenance personnel compare the perceived risk level with their own risk acceptance level to make decisions on operations. When the risk understood by the maintenance personnel is higher than the risk acceptance level, he/she chooses safe behavior. When the risk understood by the maintenance personnel is lower than the risk acceptance level, he/she will choose unsafe practices. The risk acceptance level of maintenance personnel is influenced by their own safety attitude, subjective norms, and perceived action control, based on the analysis of TPB (Li et al., 2024a). After choosing safe behavior, maintenance personnel may make mistakes in their actions due to their perception of motion control, resulting in unsafe behavior. The detailed mathematical formulations of each cognitive stage, including the equations for information acquisition, processing, response selection, and action implementation, are provided in Appendix A.

2.5. Aircraft maintenance personnel social cognition framework

There are currently two types of models regarding workers' unsafe behavior: one is Fang's cognitive model (Fang et al., 2016), which considers the influencing factors of workers' various cognitive stages and determines whether workers ultimately adopt unsafe behavior based on the probability of influencing factors. This model is comprehensive, and includes human errors and violations, but it does not consider workers' psychological factors; The second is Choi's risk perception model (Choi & Lee, 2018), in which workers compare their own risk acceptance level with the size of the risk to determine whether to adopt unsafe behavior. This subjective judgment includes manager norms and worker norms and fully reflects the psychological activities of workers when facing unsafe scenarios. However, this model does not fully consider workers' unsafe behavior and ignores whether workers detect potential safety risks in the work scenario and the influence of their own conditions and external environment on the behavior of maintenance personnel.

Therefore, by combining the advantages and disadvantages of these two models, a cognitive model of unsafe behavior among maintenance personnel that integrates about risk will be constructed. Therefore, the design concept mainly consists of the following two points: firstly, using a cognitive model as a framework, incorporating risk understanding, risk perception, risk acceptance level, and social identity in the selection response stage, and providing a detailed description of the psychological process of maintenance personnel. The second is the theory of social identity and social norms in social science theory. The definition of social identity theory is to strongly identify with a group and internalize and abide by group norms. The group norms of maintenance personnel include those of managers and colleagues. Therefore, in the model, the subjective norms of maintenance personnel are refined into manager norms and worker norms using social identity theory. In the front-line field, the subjective norms of workers are influenced by senior managers, safety managers, on-site managers, and workers. The most direct contacts with workers are colleagues and team leaders. The subjective norms in this article consider the norms of colleagues and on-site managers and express the different degrees of

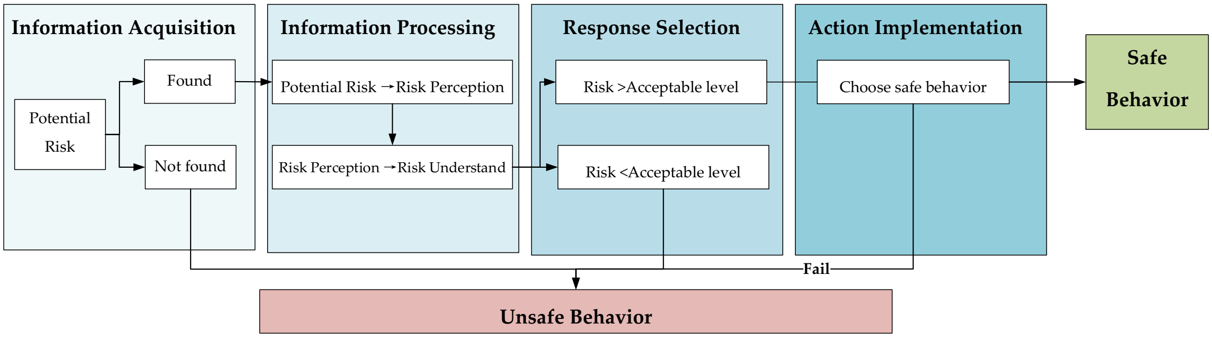

Figure 4. The sub-model of cognition for maintenance personnel

recognition of the two norms by maintenance personnel. The higher the social recognition, the more workers care about the opinions of managers and have a higher degree of recognition of their norms; The lower the social identity, the more workers care about their colleagues' opinions and have a higher degree of recognition of their norms.

As is shown in Figure 5, the interactive behaviors considered in this model include management factors, social organization factors, self factors, and environmental factors.

Management factors mainly include: (1) safety inspections to eliminate unsafe conditions; (2) Safety training affects the safety awareness and knowledge of maintenance personnel; (3) Safety guidance and control affect the management strategies of safety managers and on-site managers for maintenance personnel; (4) The team leader provided feedback to improve the safety attitude of the maintenance personnel.

Social organizational factors mainly include two types: (1) the behavior of colleagues, which affects the colleague norms of maintenance personnel; (2) The behavior of managers affects the management norms of maintenance personnel. The maintenance personnel observe the behavior of their colleagues and on-site managers to understand the current level of safety awareness and risk tolerance among the group in the project.

The main self-factors include: (1) self-accidents, and maintenance personnel adjust their safety attitude based on their behavior results. If maintenance personnel have accidents after unsafe behavior, they will be more conservative; (2) Fatigue level affects the perception of action control among maintenance personnel.

The environmental impact factors mainly refer to the external environment and working conditions of the maintenance personnel. The complete set of interaction rules among agents – including safety training, inspections, peer influence, managerial feedback, and senior management guidance – is defined in Appendix B.

3. Simulation analysis

3.1. Selection of simulation platform

In 1999, Uri Wilensky proposed the simulation platform NetLogo. It is a high-level simulation platform that uses Logo programming language and is easy to operate and learn, allowing for exploratory research on models (Chiacchio et al., 2014; Li, 2020). The multiagent interaction theory model for unsafe behavior of maintenance personnel proposed in this study, NetLogo meets its complexity, interactivity, dynamism, and closure. Therefore, NetLogo is used for multiagent ABM modelling.

3.2. Simulation model of unsafe behavior of aviation maintenance personnel

3.2.1. Development of the model

This study takes a simulated aviation maintenance scenario at the maintenance site of a medium-sized Chinese airline located at a medium-sized airport as an example. The airline operates 5 main parking bays at the airport and has an organizational structure of 74 maintenance personnel, including 10 managers. Based on actual observation data from February to May 2025, the number of frontline operators at the maintenance site during working hours typically ranges from 10 to 45. Managers usually are on duty in the office and provide on-site guidance when needed. Therefore, considering the scenario where most maintenance personnel are on duty, the simulation is set to include 40 maintenance staff and 6 managers at the maintenance site-comprising 2 senior managers, 2 safety officers, and 2 on-site supervisors, with a simulation duration of 100 days.

To ensure the accuracy of the number of personnel in the model, the following verification work was conducted. First, through on-site investigations and industry practices,

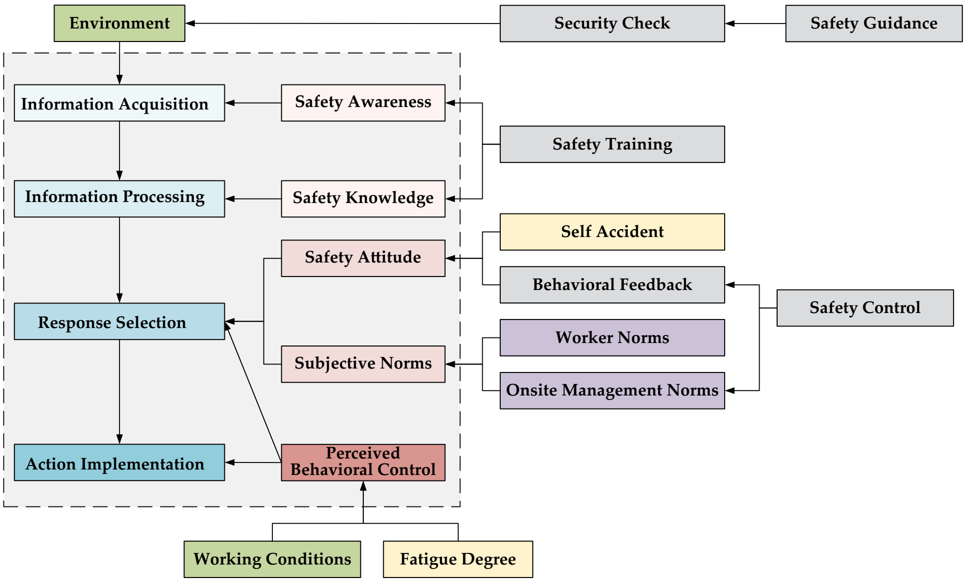

Figure 5. Aircraft maintenance personnel social cognition framework

4 airlines were was surveyed. Overall, the number of maintenance personnel an airline deploys at a specific airport is not fixed. For instance, large airlines have hundreds of aircraft at their hub bases and over 1,000 maintenance personnel; medium-sized airlines have around 100 maintenance personnel at key airports; and at transit stations, airlines only assign fewer than 30 maintenance personnel. In addition, maintenance personnel often work in shifts to ensure 24/7 coverage. The proportion of management personnel (including frontline team leaders, middle management, and senior management) among all maintenance staff typically ranges from 10% to 20%, with a common reference value deemed efficient by many companies being approximately 15%. Furthermore, these numbers and proportions are comparable to the parameter settings adopted in widely cited simulation studies on similar unsafe behaviors. For example, Zhang et al. (2025) selected 28 to 56 workers and a total of 6 managers in their construction industry model. Therefore, the selection of the above data effectively represents typical aviation maintenance scenarios to a certain extent, making the model more reflective of the situation of most airlines. Running interface in NetLogo is shown in Figure 6.

In order to ensure the reliability of the model, in the ABM simulation model, the management parameters directly measured are obtained from the actual project, while other cognitive parameters that are difficult to measure, such as safety attitude, subjective norms and other cognitive parameters, generally use hypothetical values, and carry out sensitivity analysis on these parameters to make up for their uncertainty (Yin et al., 2020). For the cognitive parameters that are difficult to measure, the normal distribution is mainly used for random selection (Bruch & Atwell, 2015). The first, when the distribution of parameters is unknown, the use of normal distribution is the most appropriate method, which fully reflects the individual differences. Secondly, the mean value of normal distribution can reflect the macro tendency of the population.

The default values of the safety attitude SAT of the maintenance personnel, the behavioral feedback BF of the team leaders, and the exemplary demonstration LE all follow a normal distribution (with a mean of 0.6 and a standard deviation of 0.1). The default values of safety awareness SA and safety knowledge also follow a normal distribution (with a mean of 0.8 and a standard deviation of 0.1). A mean of 0.8 indicates that the overall safety awareness of aviation maintenance personnel is relatively high and their safety knowledge is relatively complete.

The management norms for maintenance personnel follow a normal distribution (with a mean of 0.6 and a standard deviation of 0.1), and the norms for workers also follow a normal distribution (with a mean of 0.4 and a standard deviation of 0.1), indicating that in work sites, managers pay more attention to safety issues and have a lower acceptance of risks than workers.

The initial value of the risk understanding coefficient of maintenance personnel follows a normal distribution between 0.6 and 1.2, with an average value less than 1.0, to reflect the tendency of aviation maintenance personnel to underestimate perceived risks. The minimum value of 0.6 and the maximum value of 1.2 are derived based on the research conclusions of Choi (Choi & Lee, 2018) and Shin (Shin & Bithell, 2022). Taking the risk perception awareness (γ) as 0.5 indicates that workers refer to half of their experience and the other half to the obtained work information. Finally, the initial value of social identity follows a normal distribution (mean 0.5, standard deviation 0.1) to reflect the differences among workers.

In the NetLogo model, 1m^2 in the real world scene is set to 4 pixels, and in NetLogo, the job site is set to 1000 pixels * 200 pixels. Different sites have different project attributes, characteristics and risk sizes. Choi divides the sites into three categories according to the actual risk size: low risk 0.2, medium risk 0.5 and high risk 0.8 (Choi & Lee, 2018). The initial value of the actual safety risk is set to medium risk in this study, and the normal distribution is obeyed between 0 and 1 (mean 0.5, standard deviation 0.1).

The initial value of the safety training frequency is set to once a week, that is, once every 7 days. The initial value of the security inspection range is set to 25 meters around the safety officer. The initial value of the safety inspection intensity is set to 50%, meaning that the safety officer has a 50% chance of correcting the unsafe actions of workers

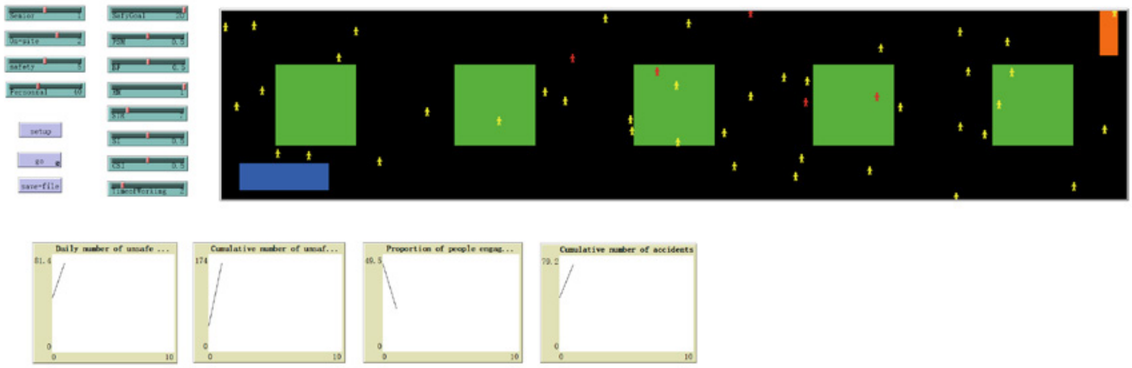

Figure 6. NetLogo simulation interface

and team leaders within the scope of the safety inspection, whilst also eliminating unsafe physical states in the surrounding environment, which reduces the exposure of hazards in the environment to 0. The initial probability of senior managers participating in safety activities is set at 50%, giving senior managers half the probability of participating in safety training activities with workers. Simultaneously, senior managers have specific safety goals for the unsafe actions recorded by safety officers each day, with the initial value set to 20 unsafe behaviors, indicating that if the number of unsafe behaviors exceeds 20 per day, the project manager will provide safety control and safety guidance to middle managers (safety officers and team leaders) to strengthen safety management. The degree of influence of worker cognitive parameters is set to 1 unit, such as ST_{SA}, etc. The learning ability of safety officers and team leaders is relatively high, and the degree of influence of safety control and guidance of the project manager is relatively strong, with SG_{SI} and other units set as 2 units.

The initial values for the model are shown in Table 5. In the benchmark model, all variables are simulated according to the initial values to reflect the cognitive process of unsafe behavior of maintenance personnel. At the same time, when studying the influence of different social organizations and management factors on the unsafe behavior of maintenance personnel, the default value of social organization parameters are changed to represent different management strategies.

Table 5. The initial value of the model

Subject	Variable	Initial value
Maintenance personnel	SA	N $(0.8,0.1^2)$
	SAT	N $(0.6,0.1^2)$
	SK	N $(0.8,0.1^2)$
	FN	N $(0.6,0.1^2)$
	WN	N $(0.4,0.1^2)$
	P	N $(0.9,0.1^2)$
	γ	0.5
	w	N $(0.5,0.1^2)$
	ST_{SK}	1
	ACC_{SAT}	1
	CW_{WN}	1
	RM_{FN}	1
	BF_{FN}	1
Site environment	AR	N $(0.5,0.1^2)$
	ER	0.0005
	SF	1
Safety officers	STR	7
	SI	0.5
	C_{SI}	0.5
	SG_{SI}	2
	SG_{CSI}	2
Onsite Management	RM	0.5
	BF	0.5
	SG_{LE}	2
	SG_{BF}	2
Senior Management	P_{SM}	50%
	SG	20

3.2.2. Validation of the model

The most general classification scheme for ABM according to their level of empirical validity has been proposed by Barde and Hoog and consists of four levels (Barde & Hoog, 2017).

Level 0: the model is a caricature of reality, as established through the use of simple graphical devices (e.g., allowing visualization of agent motions).

Level 1: the model is in qualitative agreement with empirical macrostructures, as established by plotting, e.g., the distributional properties of agent population. This is the easiest way to matching stylized facts.

Level 2: the model produces quantitative agreement with empirical macrostructures, as established through onboard statistical estimation routines.

Level 3: the model exhibits quantitative agreement with empirical microstructures, as determined from cross-sectional and longitudinal analysis of the agent population.

Among them, the macro aspect refers to group behaviors such as the overall unsafe behavior rate of maintenance personnel, while the micro aspect refers to individual behaviors such as the operational decisions of a single maintenance worker in specific maintenance scenarios. Barde and Hoog argues that the purpose of using an ABM is to provide substantial support for formulating management strategies to address phenomena in management (Barde & Hoog, 2017). In other words, the model is application-oriented rather than theory-oriented. When the modeling goal is application-oriented, the replication validity of the model must reach Level 2 or above. However, in Level 3, it is impractical to obtain all valid data on maintenance personnel's unsafe behaviors. Aviation maintenance sites typically cover multiple areas such as hangars, runways, and maintenance workshops, with a wide and scattered operation scope. Meanwhile, aircraft maintenance involves complex scenarios such as emergency tasks and nighttime troubleshooting. Unsafe behaviors are easily affected by random factors such as work pressure and fatigue, leading to temporal and spatial limitations in capturing micro-behavioral data. It is difficult for the model to accurately replicate the specific behaviors of individuals at the individual level. Therefore, this study will conduct Level 2 replication validity verification on the constructed ABM. The core logic is to conduct multi-dimensional comparisons between the model's output results and existing empirical research conclusions as well as civil aviation industry safety statistics, ensuring that the model is consistent with the real system at the qualitative and quantitative macro levels. The verification process is divided into three steps: first, confirm the basic rationality of the model through expert interviews (Level 0); second, compare the attribute characteristics such as the safety attitude and subjective norms of the maintenance personnel group with empirical research results to achieve qualitative macro consistency (Level 1); finally, benchmark the accident rate simulated by the model against authoritative industry data to achieve quantitative macro consistency (Level 2).

(1) As the foundational level of the model's empirical validity, Level 0 focuses on verifying whether the abstraction and simplification of the real system by the model align with basic logical intuition. First, the core components of the model were sorted out, including agent definition, agent attributes, interaction rules, and system constraints. On this basis, the "Expert Evaluation Scale for the Face Validity of the ABM Model" was designed, with evaluation indicators constructed from three core dimensions: first, logical consistency (whether there are contradictions in the model's rule design, and whether the agents' behavioral logic conforms to the characteristics of aviation maintenance scenarios); second, real-world relevance (whether the model's core components cover key links in maintenance safety management, and the degree of alignment with actual maintenance operation processes); third, visual intuitiveness (whether the model's graphical presentation is clear and understandable, and whether processes such as agent movement and behavioral decision-making are easy to observe). A 5-point scoring standard was set for each dimension (1 point = completely unreasonable, 5 points = completely reasonable), and an expert comment section was reserved to collect optimization suggestions.

The expert team consists of 5 members, including 3 professors in the field of aviation safety management, 1 senior engineer with more than 15 years of experience in maintenance management, and 1 expert in ABM modeling methodology, ensuring the professionalism and cross-dimensional coverage of the evaluation. The scale was distributed through a combination of email and offline meetings, and 5 valid scales were recovered. Statistical analysis showed that the average scores of the three dimensions were 4.6, 4.3, and 4.5 respectively, with an overall average score of 4.5 (a score of ≥4 is considered passing). The core expert feedback indicates that the model's agent interaction rules are consistent with the actual situation of aviation maintenance safety management, clearly presenting the action paths of key factors such as safety attitude and risk propensity on unsafe behaviors without logical contradictions. The visual process accurately reflects the core links of maintenance operations, demonstrating that the model meets the Level 0 face validity requirements and lays a foundation for subsequent higher-level validity verification.

(2) The qualitative consistency of the model at Level 1 was verified. The core phase for maintenance personnel to make decisions is the response selection stage, during which they compare the perceived risk magnitude with their own risk acceptance level to determine behavioral decisions. According to the analysis of the TPB, workers' risk acceptance is mainly influenced by safety attitude and subjective norms. Therefore, these two factors (safety attitude and subjective norms) in the model were selected for sensitivity analysis. Figures 7 and 8 respectively illustrate the impacts of safety attitude and subjective norms on maintenance personnel's risk acceptance level.

As shown in Figure 7, there is a negative correlation between safety attitude and risk acceptance level. When maintenance personnel's safety attitude score ranges from 0.8 to 1.0 (strong safety attitude), the average risk acceptance level is only 0.19. When the safety attitude score is between 0 and 0.2 (weak safety attitude), the average risk acceptance level rises to 0.52. This result is consistent with real-world logic: the stronger the maintenance personnel's safety attitude, the clearer their awareness of risks in maintenance operations (such as procedure simplification and irregular operations), and the lower their tolerance for unsafe behaviors. They are significantly more likely to choose compliant operations in key maintenance links such as engine inspections and avionics system tests, which aligns with the typical cognition in aviation safety management that "improved safety awareness reduces maintenance errors."

As shown in Figure 8, a negative correlation is also observed between subjective norms and risk acceptance level. When the subjective norm score is 0.8 to 1.0 (high safety requirements from the surrounding group), the

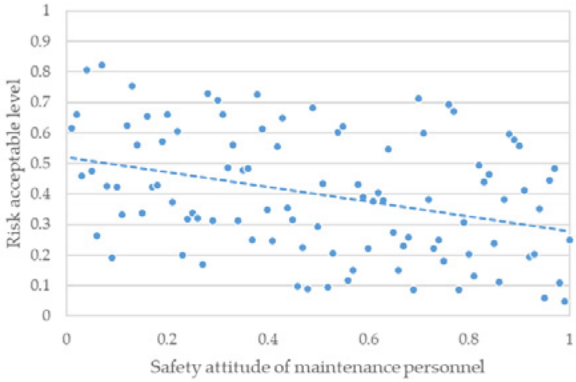

Figure 7. The relationship between safety attitude and risk acceptance in the benchmark model

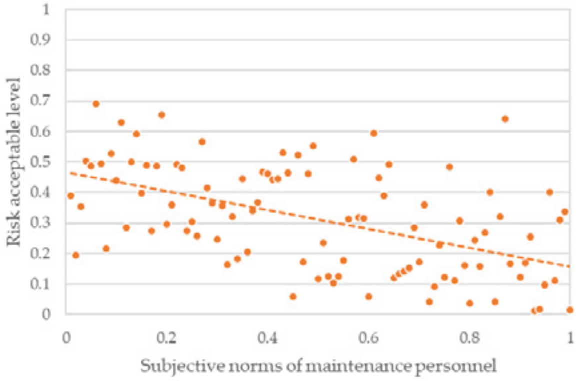

Figure 8. The relationship between subjective norms and risk acceptance in the benchmark model

average risk acceptance level of maintenance personnel is 0.24. When the subjective norm score is 0 to 0.2 (low safety requirements from the surrounding group), the average risk acceptance level reaches 0.44. This indicates that maintenance personnel's behavioral decisions are significantly influenced by the external environment, such as supervision from managers and behavioral demonstrations by colleagues. The higher the surrounding group's emphasis on safety procedures, the more maintenance personnel tend to comply with maintenance manual specifications and reduce their risk acceptance. This conclusion is consistent with the research results of Zhang et al., who stated that "subjective norms have a significant positive impact on workers' safety behaviors." (Zhang et al., 2025).

In summary, regarding the relationships between the two core variables (safety attitude and subjective norms) and risk acceptance level, the model accurately reproduces the core characteristics and typical facts of aviation maintenance safety management, maintaining qualitative consistency with existing empirical research conclusions. It has successfully met the Level 1 validity requirements.

(3) Quantitative consistency verification at Level 2 was achieved by comparing the simulation model results with empirical data. The baseline model was run through 100 independent simulations, each lasting 100 days. The final average proportion of unsafe behaviors was 0.32 (with a standard deviation of 0.05), meaning approximately 32% of maintenance operations had potential safety hazards. This result aligns with Yang et al.'s survey of 608 aviation maintenance personnel in 4 Chinese airlines where the proportion of unsafe behaviors ranged from 24.34% to 35.40% (Yang et al., 2025), which verifying the model's quantitative accuracy in predicting the proportion of unsafe behaviors.

3.2.3. Sensitivity analysis

To further verify the influence intensity of the core parameters of the model on the output results, identify the key driving factors of unsafe behaviors, and test the robustness of the model within the range of parameter fluctuations. Combining the multi-agent interaction characteristics of the model, the dimensions of the cognitive model and the design of intervention scenarios, a systematic analysis of parameter sensitivity was conducted. The "average daily proportion of unsafe behaviors" was selected as the key observation index. The single-factor sensitivity analysis method was adopted to obtain the average value of the index through 100 independent simulations (each for 100 days). The significance of the differences between groups was tested by analysis of variance (ANOVA). This analysis focuses on the output response direction, variation amplitude and potential nonlinear relationship caused by parameter changes. This design aims to analyze the influence of individual factors and directly test whether the theoretical assumptions of each module of the model (such as cognitive sub-models and environmental interactions) have been correctly implemented.

To verify the internal mechanisms of the model rather than simulate external management interventions, this section selects a total of 6 fundamental and mechanism-based parameters. These parameters reflect the inherent cognitive state of maintenance personnel, the characteristics of the external environment, and the intrinsic settings of the cognitive process, which are clearly distinguished from the management strategy parameters that are actively adjusted adjusted in the subsequent scenario analysis (such as training frequency and inspection intensity), covering the key input dimensions of the model. The specific parameters and their value ranges are shown in Table 6.

Table 6. Variable selection for sensitivity analysis

Variable	The value range of sensitivity analysis
P	0.6~1.2
γ	0~1
w	0.2~0.8
AR	0.2~0.8
ER	0.0005~0.02
Psm	0.2~0.8

Sensitivity verification of individual cognitive parameters. This section investigates the independent influence of two core cognitive parameters, risk understanding coefficient (P) and social identity (w), on the proportion of unsafe behaviors. When P varies between 0.6 (underestimating risk) and 1.2 (overestimating risk), the proportion of unsafe behavior shows a "U-shaped" curve, reaching the lowest point around P = 1.0 (accurate assessment). This result precisely verifies that "risk perception distortion" in the cognitive model is a cognitive failure link leading to unsafe behavior. When *w* increased from 0.3 (low identification) to 0.7 (high identification), the proportion of unsafe behavior decreased from 0.54 to 0.40. This indicates that the model has successfully captured the moderating effect of social identity on the internalization process of organizational norms. A higher sense of identity makes individuals more inclined to follow management norms rather than peer pressure, thereby enhancing safety compliance.

Sensitivity verification of environmental risk parameters. When AR rose from low risk (0.2) to high risk (0.8), the proportion of unsafe behavior linearly increased from 0.28 to 0.62. When ER increased from 0.0005 to 0.02, the proportion of unsafe behaviors also showed a significant upward trend. This confirms that the model is not a closed mental model but a system capable of responding reasonably to the risk level of the external working environment. The higher the environmental risk, the more systematically the probability that maintenance personnel will eventually be involved in unsafe operations, even if their cognitive status is the same. This conforms to the basic logic of the "human-machine-environment" interaction in complex systems.

Verification of the internal transformation logic of the model. The analysis of the parameter risk perception awareness (γ) reveals the nonlinear effect. When γ approaches 0 (purely experience-driven) or 1 (purely information-driven), the proportion of unsafe behaviors is relatively high. However, around $\gamma = 0.5$ (a reference for balancing experience and information), the proportion drops to the lowest level. This verifies the rationality of the "dual risk perception path" set in the model. Extreme reliance on a single cognitive source may increase the risk of judgment error, while balanced reference enhances the robustness of decision-making. The tests of parameter Psm revealed a diminishing return phenomenon. When their values exceeded a certain threshold, the reduction effect on the overall proportion of unsafe behaviors weakened significantly, which provided an internal mechanism explanation for the subsequent analysis of the "marginal effect" of safety training.

Evaluation of model output robustness. By adding ±10% random perturbations to all cognitive parameters, after 1000 simulations, the average daily proportion of unsafe behaviors was 0.34, the standard deviation was 0.06, and the coefficient of variation was 9.4% (<15%). The model output was stable and had good robustness, indicating that the model operation results had good statistical stability and repeatability. The output differences caused by parameter variations are systematic rather than random fluctuations.

In conclusion, the results of the sensitivity analysis indicate that the model's response direction to all test parameters is correct, the amplitude is reasonable, and it is highly consistent with the basic theories of cognitive psychology and safety management. This proves that the constructed ABM successfully transforms theoretical assumptions into computational logic and possesses good internal consistency and theoretical validity. The model outputs stably within a reasonable fluctuation range of parameters and has good robustness, which is used as a basis for analysis.

3.3. Intervention strategies for unsafe behaviors of aircraft maintenance personnel

To investigate the theoretical maximum potential of different intervention strategies, a series of controlled experimental scenarios was designed. These scenarios, while potentially idealized, allow for a clear comparison of the relative effectiveness of various management levers, providing a benchmark for real-world applications where factors such as compliance and resource constraints may moderate the outcomes.

3.3.1. Senior management

This part studies the intervention effect of senior managers' control on the unsafe behavior of maintenance personnel, with assuming three simulation scenarios to represent the three levels of attention paid by senior managers to the onsite safety performance.

Scenario 1: senior managers "don't pay attention to safety performance", which shows that only when the number of unsafe behaviors exceeds 20 per day, do they carry out safety control, and do not participate in each safety training ($SG = 20$, $P_{sm} = 0$).

Scenario 2: senior management "pays moderate attention to safety performance", which means that if the number of unsafe behaviors exceeds 10 every day, safety control will be carried out, and there is a half probability of participating in safety training ($SG = 10$, $P_{sm} = 0.5$).

Scenario 3: senior management "attaches great importance to safety performance" shows that safety control will be carried out every day as soon as any unsafe behaviors appeared, and every safety training will be attended ($SG = 0$, $P_{sm} = 1$).

As shown in Figure 9, the simulation results show that when senior managers "do not pay attention to safety performance", the average daily proportion of unsafe behaviors is 0.54, most of which fluctuate between 0.46 and 0.61; The average number of unsafe behaviors per day was 18.5, slightly less than the safety target of 20. When the top managers "pay moderate attention to safety performance", the average daily proportion of unsafe behaviors is 0.44, which is 19.6% lower than that of "pay little attention to safety performance", and most of them float between 0.36 and 0.51. The average number of unsafe behaviors per day was 16.9, which was 8% lower than that of "not paying attention to safety performance". When senior managers "attach great importance to safety performance", the average daily proportion of unsafe behaviors is 0.39, which is 27.2% lower than that of "do not attach importance to safety performance", and most of them float between 0.32 and 0.47. The average number of unsafe behaviors per day was 14.2, which was 23.2% lower than that of "don't pay attention to safety performance".

To determine whether the impact of senior managers' varying levels of attention to safety performance on the daily proportion of unsafe conducts is statistically significant, SPSS 27 was used to conduct an ANOVA on the core indicator of daily unsafe behavior proportion. The Tukey HSD method was applied for multiple comparison tests, with the significance level set at $\alpha = 0.05$. Results of the normality test and Levene's test for homogeneity of variances indicated that all data satisfied the assumption of normal distribution and homogeneity of variances among

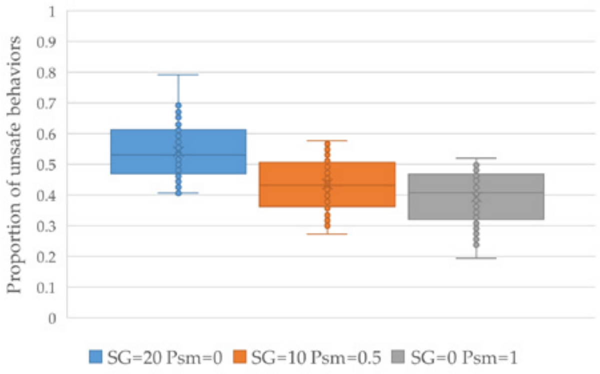

Figure 9. Proportion of unsafe behaviors under different management policies

groups, meeting the prerequisites for ANOVA. The overall ANOVA results showed a significant difference in the daily proportion of unsafe behaviors among groups with different attention levels (F = 77.201, p < 0.001), indicating that variations in senior managers' attention to safety performance do have a substantive impact on unsafe behaviors. Further results from the Tukey HSD multiple comparisons revealed specific differences: the "moderate attention" group showed a significant decrease compared to the "low attention" group (p < 0.001), and the "high attention" group had a significant reduction compared to the "low attention" group (p = 0.003).

The above statistical results verify the correlation between senior managers' attention to safety performance and unsafe behaviors. Specifically, shifting from "low attention" to "moderate attention" or "high attention" highly significantly reduces the proportion and quantity of unsafe behaviors. However, the marginal improvement effect from "moderate attention" to "high attention" is statistically less significant than that from "low attention" to "moderate attention."

The above results show that the senior managers' attention to safety performance has an important impact on unsafe behavior of maintenance personnel. However, there is little direct interaction between the senior managers and the onsite maintenance personnel, and most of them interact directly with the middle management, which affects the behavior of the maintenance personnel, and the middle management may also be slack and lazy. Therefore, the control effect of the senior managers on the unsafe behavior of the maintenance personnel is not immediate. For senior managers, the marginal utility of their degree of attention is diminishing. This diminishing return suggests that while striving for maximum attention is beneficial in theory, practical resource allocation should aim for an optimal level, such as the 'moderate attention' scenario.

3.3.2. Safety officer

This part studies the intervention effect of safety training for safety officers on unsafe operations of maintenance personnel. In the scenario simulation, taking the benchmark model as the standard, the interval of safety training is adjusted to daily (STR = 1), weekly (STR = 7), every two weeks (STR = 14), every three weeks (STR = 21) and monthly (STR = 30).

As Figure 10, the simulation results show that the more frequent the safety training, the more obvious the effect is. Compared with the monthly safety training frequency, the daily safety training frequency reduced the number of unsafe behaviors by 33.1%. However, the results also indicate a diminishing marginal effect. When the frequency of safety training is daily and weekly, the average value of both is 0.358. When the frequency of safety training is every three weeks and every month, the average value of both is around 0.517. This is because more than half of the aviation maintenance jobs need to work with certificates.

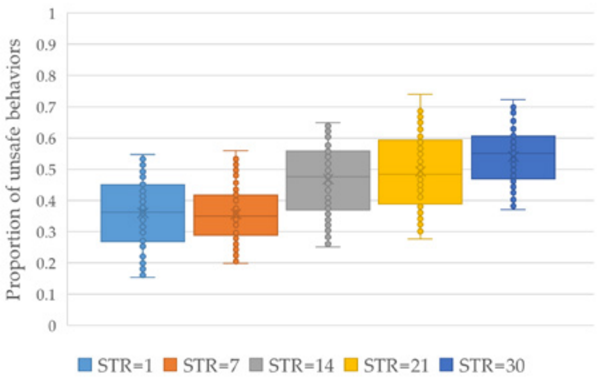

Figure 10. Proportion of unsafe behaviors at different training frequencies

Therefore, a weekly safety training frequency represents the optimal strategy, as it achieves a safety performance statistically equivalent to daily training while conserving significant organizational resources. This approach keeps the proportion of unsafe behaviors low, as shown in Figure 11, and the proportion of unsafe behaviors shows a downward trend.

Based on the learning model, the initial value of safety awareness and safety knowledge is high, and the daily safety training frequency also has a marginal effect on the enhancement effect of safety awareness and safety knowledge of maintenance personnel. Therefore, when the maintenance personnel do unsafe behaviors for other reasons but no safety accidents occur, the safety awareness will be significantly reduced and the surrounding environment will be slack, which leads to the effect of daily safety training on the unsafe behaviors of the maintenance personnel is not obvious.

To determine whether the impact of different training frequencies on the daily proportion of unsafe behaviors is statistically significant, SPSS 27 software was used to conduct a One-Way Analysis of Variance (One-Way ANOVA) on the core indicator of daily unsafe behavior proportion. The Tukey HSD method was applied for multiple compari-

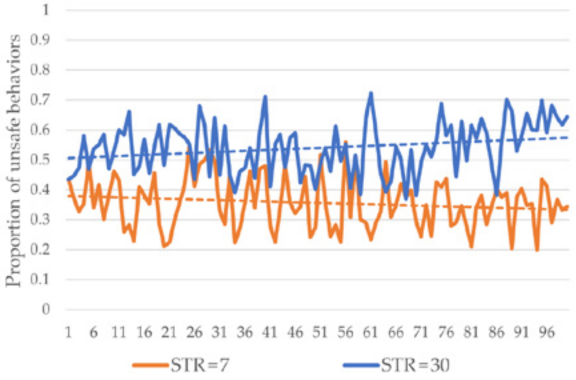

Figure 11. Proportion of daily unsafe behaviors with safety training frequency of 7 and 30

son tests, with the significance level set at $\alpha = 0.05$. Results of the normality test and Levene's test for homogeneity of variances indicated that all data satisfied the assumption of normal distribution and homogeneity of variances among groups, meeting the prerequisites for ANOVA. The overall ANOVA results showed a significant difference in the daily proportion of unsafe behaviors among groups with different safety training intervals (F = 61.477, between-group df = 4, within-group df = 496, $p < 0.001$), indicating that changes in safety training frequency are not random fluctuations but have clear statistical significance for maintenance personnel's unsafe behaviors.

Further results from the Tukey HSD multiple comparisons revealed specific differences, as shown in the Table 7. Based on the analysis, training frequencies are categorized into three types: "high frequency", "medium frequency", and "low frequency", with significant differences between each type. There were significant differences between high and low frequency groups: the mean difference between the "weekly (STR = 7)" group and the "biweekly (STR = 14)" group was 0.113 ($p < 0.001$), and the mean difference between the "biweekly (STR = 14)" group and the "triweekly (STR = 21)" group was 0.076 ($p < 0.001$). This indicates that the increase in the proportion of unsafe behaviors is statistically significant when the training interval is extended from one week to two weeks, and from two weeks to one month.

There was no significant difference within the high-frequency training group: the mean difference between the "daily (STR = 1)" group and the "weekly (STR = 7)" group was 0.003 ($p = 0.999 > 0.05$), suggesting that weekly training achieves the same behavioral control effect as daily training. There was no significant difference within the medium-frequency training group: the mean difference between the "triweekly (STR = 21)" group and the "biweekly (STR = 14)" group was 0.024 ($p = 0.491 > 0.05$), indicating that changes in training frequency have no substantive impact on behavioral improvement when the interval is between two and three weeks. These statistical results further quantify the intervention value of safety training frequency, not only verifying the intuitive rule that "higher frequency training yields better results" but also providing statistical support for "selecting weekly training as the optimal frequency", balancing safety control effectiveness and management costs.

Table 7. Impact differences of safety training intervals on unsafe behaviors

Interval of Safety Training	N	Homogeneous Subsets		
		1	2	3
STR = 7	100	.3564		
STR = 1	100	.3598		
STR = 14	100		.4691	
STR = 21	100		.4930	
STR = 30	100			.5403
Significance		.999	.491	1.000

This section studied the intervention effect of safety officers' safety inspection on the unsafe behavior of maintenance personnel. The study mainly considered two tasks of safety officers: one is to eliminate unsafe objects; the second is to correct unsafe behaviors. Based on the benchmark model, the SI of the safety inspection range and the CSI of the safety inspection intensity were adjusted from 0.1 to 1 (the values were 0.1, 0.5 and 1), and the simulation results are shown in Figure 12.

As shown in Figure 12, reducing the inspection intensity from 1 to 0.1 resulted in the proportion of unsafe behaviors increasing from 0.30 to 0.59 (an absolute increase of 0.29, or 96.3%). In comparison, a similar reduction in the inspection scope led to an increase from 0.32 to 0.63 (an absolute increase of 0.31, or 92.3%). Results of the overall ANOVA analysis and Tukey HSD multiple comparison tests indicated that different levels of safety inspection intensity and safety inspection scope both have a significant impact on maintenance personnel's unsafe behaviors ($p < 0.001$). While the relative increase is slightly larger for intensity, the narrowing of inspection scope leads to a higher final level and a marginally larger absolute increase in unsafe behaviors. From the perspective of the overall risk exposure level, the safety inspection scope has a more impact on unsafe behavior of maintenance personnel. Therefore, the simulation results indicate that both enhancing inspection intensity and the inspection scope leads to a

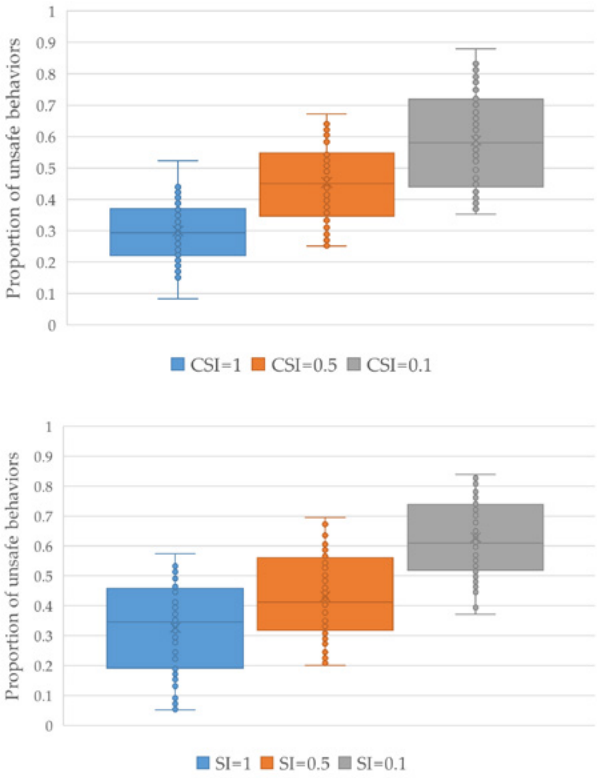

Figure 12. Proportion of unsafe behaviors of different management strategies for safety officers

significant decrease in unsafe behaviors. However, the capacity of the safety officer is limited and there is a limit to the scope or intensity of safety inspections per day. Therefore, airports use video surveillance technology to monitor unsafe behaviors and eliminate potential safety hazards, while safety officers investigate major safety hazards in the working environment on the spot.

3.3.3. Onsite management

This link studied the intervention effect of the feedback and example demonstration of the crew leader on the unsafe behavior of the maintenance personnel. First, three simulation scenarios are assumed: first, the crew leader takes himself as a safety example and encourages the maintenance personnel to work safely (RM = 0.9, BF = 0.9); Second, the person in charge of the crew sometimes does unsafe behavior and does not give feedback to the unsafe behavior of the maintenance personnel (RM = 0.5, BF = 0); Third, the crew leader worked in an unsafe way and gave negative feedback to the maintenance personnel (RM = 0.1, BF = 0.9).

As Figure 13, in scenario 1, when most of the behaviors of the crew leader are safe, and the crew members' safe behaviors are encouraged and criticized, the average proportion of unsafe behaviors of the crew members is 0.25, and the average number of unsafe behaviors per day is 14.2. In scenario 2, when the person in charge of the crew and the maintenance personnel is likely to commit unsafe acts at any time, and no feedback is given to the unsafe acts of the maintenance personnel, the average proportion of unsafe acts of the maintenance personnel is 0.41, an increase of 64.1% compared with scenario 1.

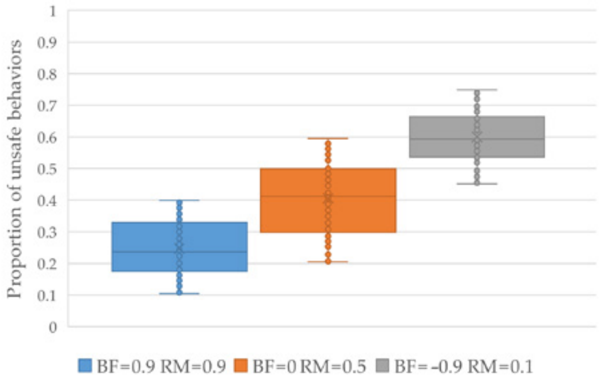

Figure 13. Proportion of unsafe behaviors under different strategies of onsite managers

When the crew leader makes unsafe behaviors and gives inefficient feedback to the maintenance personnel who have safe behaviors, and gives appreciative feedback to the maintenance personnel who have unsafe behaviors, the average proportion of unsafe behaviors of the maintenance personnel is 0.60, an increase of 143% compared with scenario 1.

Results of the normality test and Levene's test for homogeneity of variances indicated that all data satisfied the assumption of normal distribution and homogeneity of variances among groups, meeting the prerequisites for ANOVA. The overall ANOVA results showed a significant difference in the daily proportion of unsafe behaviors across different on-site management styles ($F = 339.30$, $p < 0.001$), indicating that variations in on-site managers' management styles have an impact on unsafe behaviors. Further results from the Tukey HSD multiple comparisons revealed significant differences between each pair of the three groups ($p < 0.001$). The above statistical results verify the correlation between on-site managers' different management styles and unsafe behaviors. Simulation results demonstrate that on-site management has a highly significant impact on maintenance personnel.

3.3.4. Social identity of maintenance personnel

This link studies the relationship between the social identity and safety performance of maintenance personnel. Taking the benchmark model as the standard, the parameter w(social identity) of maintenance personnel is set to $N(0.3,0.1^2)$, $N(0.5,0.1^2)$ and $N(0.7,0.1^2)$ to represent the three situations of low, medium and high social identity of maintenance personnel, and the parameter value is still selected as normal distribution to maintain the difference of simulation. As Table 8, the results show that if the strict degree of management are not distinguished, the average proportion of unsafe behavior of maintenance personnel with different social identities is: low social identity 0.565, medium social identity 0.488, high social identity 0.401, medium social identity 13.6% lower than low social identity, and high social identity 28.9% lower than low social identity.

If the strict degree of management is distinguished, the intervention effect of project management strategy "from strict to loose" in different social identity on unsafe behavior of maintenance personnel is also different: when the maintenance personnel have low and medium social identity, the proportion of unsafe behavior is reduced by 28.5% and 23.1%. When the maintenance personnel had

Table 8. Average proportion of unsafe behaviors under different social identities and levels of management strictness

Social Identity / Management	Loose management	Normal management	Strict management	Average value
Low social identity	0.673	0.540	0.481	0.565
Medium social identity	0.566	0.462	0.435	0.488
High social identity	0.488	0.401	0.314	0.401
Average value	0.576	0.468	0.410	/

a high sense of social identity, the proportion of unsafe behavior decreased by 35.7%, which is significantly higher than the first two.

Therefore, when maintenance personnel have different levels of organizational social identity, managers apply safety management in targeted ways: When maintenance personnel's social identity is relatively low, project managers not only need to adopt strict management strategies but also implement other incentive and reward measures to enhance their social identity. This is because when maintenance personnel have a high level of social identity, the intervention effect of strict project management strategies on them is more pronounced. Thus, managers should maintain maintenance personnel's social identity while using management measures to better reduce the proportion of unsafe behaviors.

3.4. Discussion

The simulation results demonstrate the efficacy of various strategies under controlled conditions. However, a gap exists between these idealized interventions and practical implementation. The following discussion elaborates on these gaps and proposes targeted measures to bridge them, thereby enhancing the real-world applicability of findings.

The senior management should adopt a "zero accident" attitude for safety management, actively participate in safety meetings such as safety training, grasp the opportunity of direct interaction with the maintenance personnel, and increase the safety knowledge and awareness of the maintenance personnel. At the same time, because the project manager and the maintenance personnel interact indirectly most of the time, the senior managers' control of safety should focus on the management of the middle management, especially the selection of the onsite manager, which significantly enhances the cost-effectiveness of safety interventions.

The frequency of safety training is recommended to be once a week, because many maintenance personnel are required to work with certificates, and their own safety knowledge and awareness are already high. At the same time, the safety training has a marginal effect on the improvement of safety quality, so the effect of safety training is not obvious. However, once the maintenance personnel make unsafe behavior but no safety accident, the effect on the reduction of safety quality will be more obvious. Therefore, safety officers should prioritize maintaining a weekly safety training schedule, while allocating additional resources to on-site inspections and the elimination of potential hazards.

The intervention effect of the inspection scope of the safety officer on the unsafe behavior of the maintenance personnel is more obvious than the inspection ability. Therefore, the video monitoring technology is added to expand the scope of the safety inspection. The safety officer with limited ability every day should inspect the key areas to eliminate the occurrence of major potential safety accidents.

Whether the effect of aviation maintenance safety management is obvious, another reason is the social identity of the maintenance personnel, that is, the recognition of the maintenance personnel for the project. If the social identity of the maintenance personnel is high, the proportion of unsafe behaviors will be maintained at the beginning of the project, and the overall safety performance will enter a better cycle. However, due to the low social identity of maintenance personnel, safety management should be strengthened. Therefore, the senior management improves the recognition of the maintenance personnel for the project, facilitate the creation of a maintenance site with a strong sense of safety atmosphere, and maintain good safety performance with weak safety management. The management pays more attention to the productivity and achieve the double goals of safety production.

Organizational culture and safety climate significantly shape aviation maintenance personnel's unsafe behaviors, though compiled model currently captures these partially. Safety climate, as a situational reflection of culture, affects perceived behavioral control. A positive climate helps turn safe intentions into actions, while a negative one weakens training effects. These factors also interact with social identity: personnel with strong organizational identification (high w) better internalize safety norms, resisting unsafe acts even if management is lax. Future models should integrate systematic culture/climate variables, as current interventions work in a specific contexts.

4. Conclusions

4.1. Main research work

A four-stage cognitive model of aviation maintenance personnel is proposed. Firstly, the research status of aviation maintenance safety management is sorted out. It is found that the research perspective in the past two years focuses on safety risks and maintenance process, while the research on unsafe behavior of aviation maintenance personnel is less. Therefore, as a breakthrough point, a four-stage cognitive model (information acquisition, information processing, response selection and action) is established, which is in line with the characteristics of aviation maintenance personnel.

A multiagent interaction model of unsafe behavior of aviation maintenance personnel was built. This paper studies the organizational structure and job responsibilities of the safety management personnel at the aviation maintenance site, which is the theoretical basis of the multiagent interaction model. Combined with the four-stage cognitive sub model of unsafe behavior of aviation maintenance personnel, the multiagent model is built. This paper describes a multiagent interaction model between aviation maintenance personnel and safety supervisors, site managers and senior managers. The model considers the main interaction rules between different managers, between different managers and frontline operators, between frontline operators and the environment, and between different managers and the environment, forming a closed loop, which has certain universality.

The multiagent interaction model is visualized by case validation and NetLogo software, and the effectiveness of the model is verified. At the same time, based on the benchmark model, different management scenarios are set for the four management methods. In the model, the intervention degree of unsafe behavior of maintenance personnel is studied by adjusting parameters, to put forward specific management opinions and future management priorities for the safety management of aviation maintenance.

4.2. Highlights

This research refines the investigation of human unsafe behavior by focusing specifically on aviation maintenance personnel. Through literature review and analysis, it is found that the current research on safety management is rarely from the perspective of unsafe actions of maintenance personnel, and the research on unsafe behavior of maintenance personnel is rarely divided into the category of "aviation maintenance personnel". Therefore, the research on the formation mechanism and intervention strategy of unsafe behavior of aircraft maintenance personnel. Therefore, this research on the formation mechanism and intervention strategy of unsafe behavior among aircraft maintenance personnel addresses a significant gap in the literature.

This study is more comprehensive in describing the cognitive factors of unsafe behavior of aviation maintenance personnel. In the multiagent interaction model of aviation maintenance personnel built in the study, four psychological factors, namely risk perception, risk understanding, social identity and risk acceptance, are considered in the selection response phase of the cognitive sub model, to better describe the psychological activities of maintenance personnel.

4.3. Limits and expectations

In the aspect of building the cognitive mechanism model of unsafe behavior of aviation maintenance personnel, this paper studies all unsafe behaviors in aviation maintenance while the risky conducts corresponding to different positions in aviation maintenance may be different. Therefore, in future research, the aviation maintenance personnel in different positions are selected to analyze their unique cognitive model of unsafe behavior. In the ABM model, the main body of aviation maintenance personnel is further classified according to their positions.

In terms of establishing the multiagent interaction theoretical model of unsafe behavior of aircraft maintenance personnel, the overall situation of the aviation maintenance site is considered in the study, but the risk exposure of different working places in the aviation maintenance site is different, that is, the probability and severity of unsafe state in different places are different. This factor is studied in detail in future simulation modeling, to more accurately simulate unsafe behaviors and safety accidents.

A key limitation of proposed model is that it assumes a neutral safety climate, which may underestimate unsafe operation rates in weak safety cultures – such as environments where safety is secondary to efficiency or error reporting is discouraged. Future research should integrate organizational metrics into the ABM systemically to more accurately simulate unsafe behavior dynamics under varied cultural contexts and precise decision support for the formulation of aviation maintenance safety management strategies.

Another remaining limitation is that some cognitive parameters (such as safety attitude initial values) rely on indirect validation (expert evaluation, literature benchmarks) rather than direct empirical data. We disclosed this gap and proposed future empirical data collection – such as 6-month on-site behavior logs and maintenance personnel safety surveys – to obtain first-hand data, enabling direct validation of model parameters and further enhancing the credibility of simulation results.

Author contributions

JW: conceptualization, methodology for the review, data screening, analysis, writing original draft.

XSH: validation of concept and methodology, validation of screened data, review of findings.

ShY: validation of analysis, data screening, and review of the original draft.

FY: project administration.

Disclosure statement

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References

Akdeniz, G., Yilmaz, H. E., & Geza, H. (2025). Cognitive and emotional impacts of face pareidolia application among pilot students. *Aerospace Medicine and Human Performance*, *96*(1), 18–22. https://doi.org/10.3357/AMHP.6428.2025

Aktas, E., & Kagnicioglu, C. H. (2023). Factors affecting safety behaviors of aircraft maintenance technicians: A study on civil aviation industry in Turkey. *Safety Science*, *164*, Article 106146. https://doi.org/10.1016/j.ssci.2023.106146

Alavosius, M. P., Houmanfar, R. A., Anbro, S. J., Burleigh, K., & Hebein, C. (2017). Leadership and crew resource management in high-reliability organizations: A competency framework for measuring behaviors. *Journal of Organizational Behavior Management*, *37*(2), 142–170. https://doi.org/10.1080/01608061.2017.1325825

Anderson, E. S., Griffiths, T. R. L., Forey, T., Wobi, F., Norman, R. I., & Martin, G. (2021). Developing healthcare team observations for patient safety (HTOPS): Senior medical students capture everyday clinical moments. *Pilot and Feasibility Studies*, *7*, Article 164. https://doi.org/10.1186/s40814-021-00891-3

Anebagilu, P. K., Dietrich, J., Prado-Stuardo, L., Morales, B., Winter, E., & Arumi, J. L. (2021). Application of the theory of planned behavior with agent-based modeling for sustainable management of vegetative filter strips. *Journal of Environmental Management*, *284*, Article 112014. https://doi.org/10.1016/j.jenvman.2021.112014

Barde, S., & Hoog, S. V. D. (2017). *An empirical validation protocol for large-scale agent-based models* (Bielefeld Working Papers in Economics and Management No. 04). SSRN. https://doi.org/10.2139/ssrn.2992473

Bruch, E., & Atwell, J. (2015). Agent-based models in empirical social research. *Sociological Methods & Research*, *44*(2), 186–221. https://doi.org/10.1177/0049124113506405

Cabuya-Padilla, D., Diaz-Lopez, D., Martinez-Paez, J., Hernandez, L., & Castaneda-Marroquin, C. (2025). SERDUX-MARCIM: Maritime cyberattack simulation using dynamic modeling, compartmental models in epidemiology and agent-based modeling. *International Journal of Information Security*, *24*, Article 122. https://doi.org/10.1007/s10207-025-00985-6

Campolettano, E. T., Bland, M. L., Gellner, R. A., Sproule, D. W., Rowson, B., Tyson, A. M., Duma, S. M., & Rowson, S. (2017). Ranges of injury risk associated with impact from unmanned aircraft systems. *Annals of Biomedical Engineering*, *45*, 2733–2741. https://doi.org/10.1007/s10439-017-1921-6

Chen, F., Fan, D., & Liu, K. (2016). Study on strategies for intervention in unsafe behavior of aviation maintenance personnel. *China Safety Science Journal*, *26*, 18–22. https://doi.org/10.16265/j.cnki.issn1003-3033.2016.07.004

Chen, Y., Wang, Y., & Wang, H. (2020). Research progress on interlaminar failure behavior of fiber metal laminates. *Advances in Polymer Technology*, 2020, Article 3097839. https://doi.org/10.1155/2020/3097839

Chiacchio, F., Pennisi, M., Russo, G., Motta, S., & Pappalardo, F. (2014). Agent-based modeling of the immune system: NetLogo, a promising framework. *Biomed Research International*, *2014*, Article 907171. https://doi.org/10.1155/2014/907171

Choi, B., & Lee, S. (2018). An empirically based agent-based model of the sociocognitive process of construction workers' safety behavior. *Journal of Construction Engineering and Management*, *144*(2), Article 16. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001421

Deng, S., Peng, R., & Pan, Y. (2022a). A cognitive failure model of construction workers' unsafe behavior. *Advances in Civil Engineering*, *2022*, Article 2576600. https://doi.org/10.1155/2022/2576600

Deng, S. W., Zhu, H. L., Peng, R., & Pan, Y. G. (2022b). Development and validation of a cognitive model-based novel questionnaire for measuring potential unsafe behaviors of construction workers. *International Journal of Occupational Safety and Ergonomics 28*(4), 2566–2573. https://doi.org/10.1080/10803548.2021.2010408

Fang, D., Zhao, C., & Zhang, M. (2016). A cognitive model of construction workers' unsafe behaviors. *Journal of Construction Engineering and Management*, *142*(9). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001118

Fogarty, G. J., & Shaw, A. (2010). Safety climate and the Theory of Planned Behavior: Towards the prediction of unsafe behavior. *Accident Analysis and Prevention*, *42*(5), 1455–1459. https://doi.org/10.1016/j.aap.2009.08.008

Fu, G., Wu, Q., Li, Y., & Wang, X. (2017). Discussion and justification of the assessment methods of the unsafe acts and the unsafe conditions. *Journal of Safety and Environment*, *17*, 994–998. https://doi.org/10.13637/j.issn.1009-6094.2017.03.035

Grimm, V., Berger, U., Calabrese, J. M., Cortes-Avizanda, A., Ferrer, J., Franz, M., Groeneveld, J., Hartig, F., Jakoby, O., Jovani, R., Kramer-Schadt, S., Munkemuller, T., Piou, C., Premo, L. S., Puetz, S., Quintaine, T., Rademacher, C., Rueger, N., Schmolke, A., Thiele, J. C., Touza, J., & Railsback, S. F. (2025). Using the ODD protocol and NetLogo to replicate agent-based models. *Ecological Modelling*, *501*, Article 110967. https://doi.org/10.1016/j.ecolmodel.2024.110967

Guo, S., Tang, B., Liang, K., Zhou, X., & Li, J. (2021). Comparative analysis of the patterns of unsafe behaviors in accidents between building construction and urban railway construction. *Journal of Construction Engineering and Management*, *147*(5). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002013

Han, Y. W., Shen, J., Zhu, X. W., & Bao, X. Y. (2025). Two-stage propagation analysis of safety risks in complex underground engineering: An integrated modeling framework. *Reliability Engineering & System Safety*, *261*, Article 111081. https://doi.org/10.1016/j.ress.2025.111081

Hobbs, A., & Williamson, A. (2002). Unsafe acts and unsafe outcomes in aircraft maintenance. *Ergonomics*, *45*(12), 866–882. https://doi.org/10.1080/00140130210148528

Hong, Y., Kim, M. J., & Sohn, Y. W. (2023). The Relationship between Job Insecurity and Safety Behavior: The Buffering Role of Leadership Ethics. *Sustainability*, *15*(18), Article 13910. https://doi.org/10.3390/su151813910

Huang, L., Wu, C., Wang, B., Ouyang, Q., & Lin, H. (2019). An unsafe behaviour formation mechanism based on risk perception. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *29*(2), 109–117. https://doi.org/10.1002/hfm.20762

Huang, W. D., & Cui, Y. (2019). Effect of individual cognitive behavior model on public opinion communication mechanism based on social ecosystem. *Ekoloji*, *28*, 4723–4730.

Innocenti, E., Delhom, M., Idda, C., Gonsolin, P.-R., & Urbani, D. (2021). Agent-based modelling of the spread of COVID-19 in Corsica. In *IEEE Symposium Series on Computational Intelligence* (*SSCI*). IEEE. https://doi.org/10.1109/SSCI50451.2021.9660184

Jiang, S. Q., Chen, W. J., Kang, Y. T., Liu, J. H., & Kuang, W. L. (2021). Identifying cognitive mechanism underlying situation awareness of pilots' unsafe behaviors using quantitative modeling. *International Journal of Environmental Research and Public Health*, *18*(6), Article 3052. https://doi.org/10.3390/ijerph18063052

Jin, P. J., Guo, S. H., & Li, C. Q. (2025). Center-of-gravity-aware graph convolution for unsafe behavior recognition of construction workers. *Sensors*, *25*(17), Article 5493. https://doi.org/10.3390/s25175493

Li, B., Tang, S. F., & Li, W. Y. (2025). Real-time recognition of miner unsafe behaviors via skeleton-based spatiotemporal modeling with Mamba. *Journal of Real-Time Image Processing*, *22*, Article 188. https://doi.org/10.1007/s11554-025-01764-1

Li, L., Zhao, Y., Cao, Y., Chen, Y., & Qi, J. (2023). Influencing factors and functions of unsafe behavior propagation of civil aviation maintenance personnel. *Journal of Safety and Environment*, *23*, 4435–4441. https://doi.org/10.13637/j.issn.1009-6094.2022.2167

Li, M., Yuan, C., Li, K., Gao, M., Zhang, Y., & Lv, H. (2024a). Knowledge management model for urban flood emergency response based on multimodal knowledge graphs. *Water*, *16*(12), Article 1676. https://doi.org/10.3390/w16121676

Li, X. (2020). Influence of different parameter on the spread of COVID-19 based on NetLogo. In *International Conference on Artificial Intelligence and Computer Engineering* (*ICAICE*) (pp. 315–318), Beijing, China. IEEE. https://doi.org/10.1109/ICAICE51518.2020.00067

Li, X., Qiu, Z., Liu, Q., Zhang, X., and Zhang, Y. (2024b). Research on the propagation mechanism of Miners' unsafe behavior based on subject heterogeneity. *Operations Research and Management Science*, *33*, 220–226.

Liang, Q., Feng, M. L., & Leung, M. Y. (2025). Exploring pathways to unsafe behaviors under stress: Identifying safety antecedent factors and configuration analyses. *Engineering Construction and Architectural Management*, 1–23. https://doi.org/10.1108/ECAM-01-2025-0016

Maneechaeye, P., & Potipiroon, W. (2022). The impact of fleet-level and organization-level safety climates on safety behavior among Thai civilian pilots: The role of safety motivation. *Safety Science*, *147*, Article 105614. https://doi.org/10.1016/j.ssci.2021.105614

Mezentseva, A., Gracia, F. J., Silla, I., & Martínez-Córcoles, M. (2023). The role of empowering leadership, safety culture and safety climate in the prediction of mindful organizing in an air traffic management company. *Safety Science*, *168*, Article 106321. https://doi.org/10.1016/j.ssci.2023.106321

Ni, G., Yang, L., An, Y., & Zheng, Y. (2024). Contagion mechanism of unsafe behavior information in groups of construction workers. *China Safety Science Journal (CSSJ)*, *34*, 43–52. https://doi.org/10.16265/j.cnki.issn1003-3033.2024.01.2491

Ni, G. D., Zhang, Q., Fang, Y. Q., Zhang, Z. Y., Qiao, Y. N., Wang, W. S., & Deng, Y. L. (2023). How resilient safety culture correct unsafe behavior of new generation of construction workers: the mediating effects of job crafting and perceived work meaningfulness. *Engineering Construction and Architectural Management*, *30*, 4821–4845. https://doi.org/10.1108/ECAM-04-2022-0325

Peker, M., Dogru, O. C., & Mese, G. (2022). Role of supervisor behavioral integrity for safety in the relationship between top-management safety climate, safety motivation, and safety performance. *Safety and Health at Work*, *13*(2), 192–200. https://doi.org/10.1016/j.shaw.2022.03.006

Racca, A. R., Sulis, E., & Capecchi, S. (2022). Behavioral web tracking in e-learning: An educational process mining application. In *26th International Conference Information Visualisation* (*IV*) (pp. 269–274), Vienna, Austria. IEEE. https://doi.org/10.1109/IV56949.2022.00053

Shin, H., & Bithell, M. (2022). Exposure to non-exhaust emission in Central Seoul using an agent-based framework. In M. Czupryna & B. Kaminski, *Advances in social simulation* (pp. 343–354). Springer. https://doi.org/10.1007/978-3-030-92843-8_26

Sun, N. H., & Tong, R. P. (2025). A century of inquiry in industrial safety: Intellectual genealogy and future prospects in unsafe behavior research. *Safety Science*, *191*, Article 106971. https://doi.org/10.1016/j.ssci.2025.106971

Tyagi, A., Tripathi, R., & Bouarfa, S. (2023). Safety management system and hazards in the aircraft maintenance industry: A systematic literature review. *Aviation*, *27*(3), 212–224. https://doi.org/10.3846/aviation.2023.19851

Wachter, J. K., & Yorio, P. L. (2014). A system of safety management practices and worker engagement for reducing and preventing accidents: An empirical and theoretical investigation. *Accident Analysis and Prevention*, *68*, 117–130. https://doi.org/10.1016/j.aap.2013.07.029

Wang, Y., & Hou, X. (2015). Study on influence to unsafe behavior of aircraft maintenance personnel by maintenance resource management based on SEM. *Journal of Safety Science and Technology*, *11*, 110–115.

Wu, T. C., Lin, C. H., & Shiau, S. Y. (2010). Predicting safety culture: The roles of employer, operations manager and safety professional. *Journal of Safety Research*, *41*(5), 423–431. https://doi.org/10.1016/j.jsr.2010.06.006

Wu, X., Li, X., Chen, J., Gao, J., & Luo, X. (2024). Driving mechanism of attentional bias toward safety of construction workers: Case study in China. *Engineering Construction and Architectural Management*, *33*(1), 125–143. https://doi.org/10.1108/ECAM-03-2024-0370

Xiao, Q., Luo, F., Li, Y., & Pan, D. (2023). Risk prediction and early warning of pilots' unsafe behaviors using association rule mining and system dynamics. *Journal of Air Transport Management*, *110*, Article 102422. https://doi.org/10.1016/j.jairtraman.2023.102422

Yang, C., Wei, W., Bai, H., Liu, P., Ji, M., & You, X. (2025). The relationship between sense of calling and safety behaviors of aircraft maintenance technicians: A moderated mediation model. *Studies of Psychology and Behavior*, *23*, 714–720.

Yang, C. C., Liu, P., Xu, S., Xie, X. D., Li, X. H., Bai, H., Ji, M., & You, X. Q. (2024). Exploring positive psychological factor on safety behavior of Chinese aircraft maintenance technicians: The interplay of workplace well-being, work engagement, and leadership. *Safety Science*, *175*, Article 106523. https://doi.org/10.1016/j.ssci.2024.106523

Yi, T., Dong, Y., & Li, J. Z. (2025). Leadership in the darkness: Unveiling the impact of exploitative tactics on Miners' unsafe behaviors. *Safety Science*, *188*, Article 16. https://doi.org/10.1016/j.ssci.2025.106873

Yin, X., Xu, X., & Chen, X. (2020). Risk mechanisms of large group emergency decision-making based on multi-agent simulation. *Natural Hazards*, *103*, 1009–1034. https://doi.org/10.1007/s11069-020-04023-7

Zhang, Z. T., Guo, H. L., Gao, P. Z., Wang, Y., & Fang, Y. H. (2023). Impact of owners' safety management behavior on construction workers' unsafe behavior. *Safety Science*, *158*, Article 105944. https://doi.org/10.1016/j.ssci.2022.105944

Zhang, Z. T., Guo, H. L., Li, H., & Fang, Y. H. (2025). Agent-based simulation approach to analyzing the impact of construction safety management behaviors on workers' safety behaviors. *Journal of Construction Engineering and Management*, *151*(8), Article 15. https://doi.org/10.1061/JCEMD4.COENG-15977

Zhao, C., Li, H., Zhang, W., Dai, J., & Dong, L. (2024). Risk identification and safety assessment of human-computer interaction in integrated avionics based on STAMP. *Journal of Systems Engineering and Electronics*, *35*(3), 689–706. https://doi.org/10.23919/JSEE.2024.000031

APPENDIX

A. Cognition model of aircraft maintenance personnel behavior

Information acquisition stage

In the information acquisition stage, the main cognitive influencing factor for aircraft maintenance personnel is safety awareness. In the workplace, maintenance personnel detects potential safety risks through their sensory organs. The higher the safety awareness, the greater the probability that maintenance personnel will identify potential safety risks.

$$FR_i^t = \begin{cases} 0, & Rand(0,1) \geq SA_i^t \\ 1, & Rand(0,1) < SA_i^t \end{cases}, \tag{1.1}$$

where, SA_i^t represents the safety awareness of maintenance personnel *i* at time *t*; the higher the safety awareness, the stronger the ability of maintenance personnel to identify risks. FR_i^t indicates whether maintenance personnel i has detected potential risks at time t: 1 means potential safety risks are detected, and the process proceeds to the next stage; 0 means no potential safety risks are detected, leading to unsafe behaviors.

Information processing stage

After detecting potential hazard information, maintenance personnel's risk perception is derived from the actual safety risk level in the external environment and the information stock in their temporary memory and knowledge base. The magnitude of perceived risk is shown in Equation (1.2).

$$PR_i^t = \frac{\gamma}{t-1}\sum_{k=1}^{t-1} PR_i^k + \left(1-\gamma\right) AR_i^t, \tag{1.2}$$

where, PR_i^t is the risk perceived by maintenance personnel i at time t; $\frac{\gamma}{t-1}\sum_{k=1}^{t-1} PR_i^k$ is the risk previously perceived by maintenance personnel, which becomes the source of their temporary memory and knowledge base for the next day; AR_i^t is the actual risk level encountered by maintenance personnel i at time t; γ is the risk perception awareness of maintenance personnel. The stronger the risk perception awareness, the greater the dependence of maintenance personnel on past experience. According to the theory of bounded rationality in cognition, limitations in the individual cognitive process may lead maintenance personnel to underestimate or overestimate risks, and the risk level understood by maintenance personnel may not equal the perceived risk. The risk level understood by maintenance personnel is shown in Equations (1.3) and (1.4).

$$P_i^t = P_i^{t-1} + \left(SK_i^t - SK_i^{t-1}\right); \tag{1.3}$$

$$UR_i^t = P_i^t PR_i^t, \tag{1.4}$$

where, SK_i^t represents the safety knowledge of maintenance personnel i at time t; more safety knowledge means a stronger ability to understand risks. UR_i^t is the risk level understood by maintenance personnel i at time t. P_i^t is the risk understanding coefficient of maintenance personnel i at time t: if P_i^t is greater than 1, the risk understood by maintenance personnel i at time t is higher than the perceived risk; if P_i^t is less than 1, the understood risk is lower than the perceived risk. Changes in maintenance personnel's safety affect their level of understanding of risk magnitude. In the workplace, maintenance personnel's subjective norms are generally influenced by senior managers, safety managers, on-site managers, and colleagues. Since the application of subjective norms in the cognitive model of maintenance personnel involves observing the behaviors of colleagues and on-site managers during work or being influenced by their feedback, this paper only considers colleague norms and on-site manager norms as subjective norms.

Response selection stage

In the response selection stage, maintenance personnel make behavioral decisions by comparing the understood risk level with their own risk acceptance. When the understood risk is higher than the risk acceptance level, they choose safe behaviors; when the understood risk is lower than the risk acceptance level, they choose unsafe behaviors. Based on TPB, maintenance personnel's risk acceptance is affected by their safety attitude, subjective norms, and perceived behavioral control.

$$CB_i^t = \begin{cases} 0, & RA_i^t \le UR_i^t \\ 1, & RA_i^t > UR_i^t \end{cases}; \tag{1.5}$$

$$RA_i^t = a_1 * \left(1 - SAT_i^t\right) + a_2 * \left(1 - SN_i^t\right) + a_3 * PBC_i^t + \varepsilon, \tag{1.6}$$

where, RA_i^t is the risk acceptance level of maintenance personnel i at time t; SN_i^t is the subjective norm of maintenance personnel i at time t; PBC_i^t is the perceived behavioral control of maintenance personnel i at time t; a_1, a_2, and a_3 respectively represent the influence weights of changes in safety attitude, subjective norms, and perceived behavioral control on the response selection stage of maintenance personnel; ε is a random influence factor, representing random fluctuations in risk acceptance caused by unexplainable external influences, reflecting the bounded rationality of maintenance personnel's cognition; CB_i^t indicates whether maintenance personnel choose unsafe behaviors: 1 means choosing unsafe behaviors, and 0 means choosing safe behaviors. In the workplace, maintenance personnel have the most direct contact with colleagues and front-line managers., as shown in Equation (1.7).

$$SN_i^t = \left(1 - \omega_i\right) WN_i^t + \omega_i FN_i^t, \tag{1.7}$$

where, WN_i^t represents the colleague norm perceived by maintenance personnel i at time t; represents the on-site manager norm perceived by maintenance personnel i at time t; ω_i is the social identity of maintenance personnel, indicating their recognition of the project. A higher ω_i means maintenance personnel care more about managers' opinions and have a higher recognition of manager norms; a lower ω_i means they care more about colleagues' opinions and have a higher recognition of colleague norms.

Action execution stage

Even after choosing safe behaviors, maintenance personnel may make operational errors due to their perceived behavioral control capabilities, resulting in unsafe behaviors.

$$UB_i^t = \begin{cases} 0, & Rand\left(0,1\right) \ge PBC_i^t \; and \; CB_i^t = 0 \\ 1, & Rand\left(0,1\right) < PBC_i^t \; and \; CB_i^t = 0 \end{cases}. \tag{1.8}$$

The perceived behavioral control PBC_i^t of maintenance personnel i at time t is the product of working conditions and physical conditions, as shown in Equations (1.9) and (1.10).

$$PBC_i^t = SF_i^t * \left(1 - FA_i^t\right); \tag{1.9}$$

$$FA_i^t = \left(1 - i_m\right)^n + \varepsilon_i . \tag{1.10}$$

In Equation 1.9, FA_i^t is the accumulated fatigue of maintenance personnel *i* at time *t*, reflecting their physical conditions; SF_i^t is the working environment condition of maintenance personnel *i* at time *t*. Higher work burnout is more likely to lead to unsafe behaviors, so accumulated fatigue is negatively correlated with unsafe behaviors. In Equation (1.10), *n* represents the daily working duration; i_m is the state decay rate, ranging from 5% to 10%; ε_i is the initial value, indicating that different maintenance personnel have different pressure-bearing capacities.

Accident occurrence stage

A safety accident refers to the probability of injury or death of each maintenance personnel, from the perspective of individual maintenance personnel. The behavioral description of whether a maintenance personnel member has an accident is shown in Equation (1.11).

$$accident_i^t = \begin{cases} 0,\ \left(UB_i^t = 0\, and\, Rand\left(0,1\right) \geq ER_i^t\right) or \left(UB_i^t = 0\right) \\ 1,\ UB_i^t = 1\ and\, Rand\left(0,1\right) \leq ER_i^t \end{cases}, \tag{1.11}$$

where, ER_i^t is the hazard exposure degree of maintenance personnel *i* at time *t*; a higher value indicates a greater probability of maintenance personnel being in an unsafe physical state; $accident_i^t$ indicates whether maintenance personnel *i* has an accident at time *t*: 1 means an accident occurred, and 0 means no accident occurred.

B. Interaction rules

Workplace safety management strategies affect safety performance by influencing the cognitive level of maintenance personnel, and maintenance personnel's cognition serves as an intermediary between safety performance and safety management. The workplace safety management system is negatively correlated with the accident rate: the stronger the safety management intensity, the lower the on-site accident rate. The safety management system and maintenance personnel's cognition is used to study the development trend of safety performance.

Accident consequences

Safety accidents occurring to maintenance personnel in the workplace will affect their safety attitudes. If unsafe behaviors of maintenance personnel do not result in safety accidents, their safety vigilance towards unsafe behaviors will relax in subsequent behavioral choices, leading to a decline in safety attitude (*SAT* decreases by ACC_{SAT} units). Conversely, if unsafe behaviors cause safety accidents, they will become more risk-averse and make more conservative behavioral choices, leading to an increase in safety attitude (SAT increases by SAT_i^t units).

$$SAT_i^{t+1} = \begin{cases} SAT_i^t + ACC_{SAT},\ UB_i^t = 1 and\, accident = 1 \\ SAT_i^t - ACC_{SAT},\ UB_i^t = 1 and\, accident = 0 \end{cases}. \tag{2.1}$$

Safety training

Safety training refers to providing maintenance personnel with targeted, effective, and reasonably frequent learning opportunities to master safe operation methods, develop safe work habits, thereby improving their safety awareness and ability to respond to emergencies, and enriching their safety knowledge. Safe behaviors involve processes of learning, execution, forgetting, and re-learning, so the frequency and intensity of training are crucial. The ideal state is to reduce the forgetting rate or failure rate of learned content to a tolerable level. Safety training updates the safety knowledge (*SK*) and safety awareness (*SA*) of maintenance personnel. Each safety training increases the value of *SK* by SOT_{SK} units and *SA* by SOT_{SA} units.

$$SK_i^{t+1} = SK_i^t + SOT_{SK}; \tag{2.2}$$

$$SA_i^{t+1} = SA_i^t + SOT_{SA}. \tag{2.3}$$

Safety inspections

Safety inspections refer to the frequency and intensity of safety officers' inspections on on-site hazard sources and maintenance personnel's unsafe behaviors. Conducting daily and special safety inspections and patrols is a guarantee of safety. Firstly, it directly corrects maintenance personnel's unsafe behaviors; secondly, it eliminates faults in on-site mechanical equipment to reduce unsafe physical states. Therefore, in the model, safety officers must eliminate hazard sources within a certain range (*SI*) and correct unsafe behaviors of maintenance personnel within a certain range every day, with a probability (C_{SI}) of successful observation and correction.

Influence of colleagues' behaviors

Maintenance personnel's unsafe behaviors are not only affected by the management strategies of senior managers but also by colleagues. The behaviors of surrounding colleagues largely influence maintenance personnel's behavioral choices. If a colleague *k* around maintenance personnel *i* engages in unsafe behaviors, it will have the following negative impacts on *i*: first, *i* will perceive that the colleague approves of unsafe behaviors; second, *i* may lack sufficient experience to learn from the colleague's inappropriate practices. If a colleague *k* around *i* engages in safe behaviors, it will have the following positive impacts: first, *i* will perceive that the colleague disapproves of unsafe behaviors and values team safety; second, *i* may lack sufficient experience to learn from the colleague's safe practices. In this interaction, maintenance personnel update the colleague norm (*WN*) through a learning model: if a colleague engages in unsafe behaviors, WN_i^t of *i* decreases by CW_{WN} units; otherwise, it increases by CW_{WN} units.

$$WN_i^{t+1} = \begin{cases} WN_i^t + CW_{WN},\ UB_i^t = 0 \\ WN_i^t - CW_{WN},\ UB_i^t = 1 \end{cases}. \tag{2.4}$$

Feedback and demonstration by on-site managers

On-site managers have a significant impact on maintenance personnel's behaviors. Two main behaviors of on-site managers – behavioral feedback and exemplary demonstration – update the manager norm (*FN*) of maintenance personnel.

$$FN_i^{t+1} = \begin{cases} \begin{cases} FN_i^t - LE_{FN},\ UB_i^t = 0\, and\, BF_i^t < 0 \\ FN_i^t + LE_{FN},\ UB_i^t = 0\ and\, BF_i^t > 0 \end{cases} \\ \begin{cases} FN_i^t \qquad\qquad ,\ UB_i^t = 1 and\, BF_i^t < 0 \\ FN_i^t - LE_{FN},\ UB_i^t = 1 and\, BF_i^t > 0 \end{cases} \end{cases}. \tag{2.5}$$

Guidance and control by senior managers

For senior managers, safety is a primary and non-negotiable goal. They receive daily statistics from safety officers on the number of unsafe behaviors and accidents and compare them with the upper limit of tolerable safety performance. If the number of unsafe behaviors on the previous day exceeds the safety goal (*SG*), senior managers will issue warnings to safety officers, increasing the safety inspection intensity (C_{SI}) and inspection range (*SI*) on the next day to reduce potential on-site safety risks; they will also issue warnings to on-site managers, enhancing the intensity of behavioral feedback (*BF*) and exemplary demonstration (*LE*).

$$LE_i^{t+1} = LE_i^t + SG_{LE}; \tag{2.6}$$

$$BF_i^{t+1} = BF_i^t + SG_{BF}; \tag{2.7}$$

$$CSI_i^{t+1} = CSI_i^t + SG_{CSI}; \tag{2.8}$$

$$SI_i^{t+1} = SI_i^t + SG_{SI}. \tag{2.9}$$

Senior managers' participation in safety activities

Senior managers have a probability (P_{SM}) of deciding whether to participate in each safety training session. If they participate, the effectiveness of the safety training will be enhanced: *SK* will increase by an additional SOT_{SK} units, and *SA* will increase by an additional SOT_{SA} units, as shown in Equations (2.10) and (2.11).

$$SK_i^{t+1} = SK_i^t + SOT_{SK}; \tag{2.10}$$

$$SA_i^{t+1} = SA_i^t + SOT_{SA}. \tag{2.11}$$