Unstable approach in aviation : causal factors and preventive interventions

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**UNSTABLE APPROACH IN AVIATION: CAUSAL
FACTORS AND PREVENTIVE INTERVENTIONS**

LAI HSUEH-YI

School of Mechanical and Aerospace Engineering

2019

**UNSTABLE APPROACH IN AVIATION: CAUSAL
FACTORS AND PREVENTIVE INTERVENTIONS**

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School of Mechanical and Aerospace Engineering

A thesis submitted to Nanyang Technological University in
partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research,
is free of plagiarised materials, and has not been submitted for a higher degree to any
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Hsueh-Yi Lai

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

26 / 7 / 2019

AP Chen Chun-Hsien

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Authorship Attribution Statement

This thesis contains material from 3 paper(s) published in the following peer-reviewed journal(s) in which I am listed as the first author.

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The contributions of the co-authors are as follows:

- Prof Chun-Hsien Chen and Prof Li-Pheng Khoo guide the experiment design and project direction.
- Mr. Lai, Hsueh-Yi conducted the experiments and prepared the manuscript drafts.

The manuscript was revised by Dr. Pai Zhang

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- Prof Chun-Hsien Chen and Prof Li-Pheng Khoo guide the experiment design and project direction.
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- Mr. Lai, Hsueh-Yi conducted the experiments and prepared the manuscript drafts.

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List of Abbreviations

ATCO:	Air Traffic COntroller
ABM:	Agent-Based Modelling
CDM:	Critical Decision Method
DES:	Discrete Event Simulation
DH:	Decision Height
EFA:	Exploratory Factor Analysis
FETC:	Framework of Evolving Team Cognition
FAF:	Final Approach Fix
IAF:	Initial Approach Fix
ICAO:	International Civil Aviation Organization
ICMM:	Individually Constructed Mental Model
MANOVA:	Multivariate ANalysis Of Variance
MMD:	Mental Model Disconnect
MMIC:	Mental Models of Integrated Care
MTS:	Multi-Team System
SA:	Situation Awareness
SD:	System Dynamics
STAR:	Standard Terminal Arrival Route
SMM:	Shared-Mental Model
TCAS:	Terrain Collision Avoidance System

Publication list

Journal papers

1. **Lai, H.-Y.**, C.-H. Chen, L.-P. Khoo, and P. Zheng, *Unstable approach in aviation: Mental model disconnects between pilots and air traffic controllers and interaction conflicts*. Reliability Engineering & System Safety, 2019. **185**: p. 383-391.
2. **Lai, H.-Y.**, C.-H. Chen, P. Zheng, and L.-P. Khoo, *Towards better information transparency in the air traffic landing system: A novel agent-based model with implicit interactions*. Reliability Engineering & System Safety, 2019. **191**: Article 106569.
3. **Lai, H.-Y.**, C.-H. Chen, P. Zheng, and L.-P. Khoo, *Investigating the evolving context of an unstable approach in aviation from mental model disconnects with an agent-based model*. Reliability Engineering & System Safety, 2020. **193**: Article 106657.

Conference papers

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Abstract

Landing safety has long been a concern in commercial airlines. In a landing system, a team with heterogeneous operators, including pilots and air traffic controllers (ATCOs), is required to collaboratively accomplish safe landing. The landing without satisfying stable approach criteria, known as unstable approach, may cause severe economic losses or even casualties. Therefore, the occurrence of an unstable approach has attracted research attention, which highlights the necessity of improving the quality of a landing system. To study the mechanism of such system failures, the quality of team interaction plays a critical role. Specifically, the synchronization of the team members' respective shared mental models (SMMs) is compulsory for the development of holistic team cognition. The mental model disconnects (MMDs) among the team members cause interaction conflicts, jeopardizing a system's reliability and performance. Accordingly, this research aims to study the contextual relationship among the occurring MMDs in order to pinpoint the root causes of the failures in a landing system that need to be mitigated. To fill the gaps, role-specific SMMs and the framework of evolving team cognition (FETC) are accordingly proposed. Three consecutive research efforts are performed in this thesis, namely, MMD mapping, implementation of FETC in an unstable approach, and investigation into better

information transparency in a landing system. First, in MMD mapping, the exact items of the MMDs are extracted using a crew-based critical decision method. With the MMDs in the task-related SMM, a team may face difficulty in integrating the respective working results during an implicit interaction, which requires further negotiation to coordinate each other's requirements. On the contrary, due to the possible MMDs in the team-related SMM, a team may fail to conduct the interaction by taking proper actions or critical information during an explicit interaction. This might result in the team missing the window to intercept landing risks from evolving. Furthermore, a new type of MMDs, called conflicting disconnects, are identified in contingent scenarios such as unexpected weather change. This MMD highlights the possible contradiction of the respective requirements between parties. Based on the above findings, the proposed FETC is successfully implemented in an unstable approach. This work applies agent-based modeling (ABM) to simulate the interaction of autonomous team members. The result shows that the occurrence of MMDs during interaction is relatively frequent around the terminal area. A strong relationship between team-related MMDs and landing instability is found, which explains 40% of the variance in exploratory factor analysis. Specifically, two major categories of team-related MMDs are classified, namely passive information dissemination and late initiation of corrective interaction. Considering both MMDs, a landing system's sensitivity and reliability are further

addressed to conduct satisfactory error detection and correction. Accordingly, further research towards better information transparency in a landing system is conducted to study the positive effects of information transparency on a landing system's performance. To eliminate the information gaps that impede a system's information transparency, the information required for parties to make decisions in level 1 situation awareness (SA) is shared for operators to mutually monitor possible goal changes in response to changing conditions. Dynamic goal sharing facilitates a team to conduct both implicit and explicit interactions in a proactive manner. To examine how a landing system is positively affected, two agent-based models are accordingly developed to simulate the current and improved landing system. Based on the simulation results, better information transparency greatly reduces the demands of refractive interaction, reflecting a reduction in system errors. Furthermore, the efficiency of resource utilization is further improved without causing significant delay. To facilitate the knowledge obtained further, future research aims to study how the mutual information in a team facilitates the operators' role-specific SMMs, which is dedicated to identify the critical information needed to be shared in a team.

1 . Introduction

This chapter first presents the overall background and research gaps in landing safety in the aviation system. Then, research objectives and scopes are accordingly identified. Lastly, the organization of this thesis is presented.

1.1 Background

In the aviation industry, the quality of air traffic control has long been a critical concern. Relevant research indicated that by 2025, the number of operating flights will be twice as many as in 2006 [1]. This reflects an urgent need to improve air traffic flow management. This issue is particularly crucial for the aircraft landing phase. A historical report showed that 42% of fatal accidents occurred in the landing phase, making it the phase with the highest accident rate among all the phases of a flight [2]. Accordingly, the landing system is subject to errors. The time pressure, limited airspace, and uncertainties lead to frequent changes in an aircraft's flight state and high workload [3-6]. Specifically, relevant research indicated that most of the landing accidents have a strong relationship with an unstable approach or late go-around [7-10]. Furthermore, research indicated that an unstable approach was a causal factor in 40% of approach accidents [11]. Accordingly, relevant issues regarding unstable approaches should be carefully examined for not only improving landing safety but also satisfying the

increasing demands in the future.

Much of the relevant literature has focused on the decision-making and performance of pilots [12-16]. Numerous studies have indicated that impaired situational awareness (SA) because of an excessive mental workload significantly degrades the quality of decision-making [14, 17, 18]. Moreover, the extremely low probability of occurrence of a serious accident leads to continuation bias [11, 19]. Pilots are surely responsible for avoiding unstable landings; however, air traffic controllers (ATCOs) may also play a significant role. Pilots' operations are always subject to ATCO instructions that are based on maintaining separation between planes [20]. Thus, team interaction should also play a critical role in landing safety [21]. However, high-quality interaction between pilots and ATCOs can be challenging. First, the inevitable time pressure and frequent changes in the flight path during the approach phase strain the ability of operators to execute dynamic interactions [22, 23]. By contrast, because of operators' heavy workload and inefficient one-to-one radio channels, managing the mental workload of operators is stressful [5, 12, 24], impairing the ability of the flight team to achieve proper interactions. Mosier et al. [23] documented that 52% of communication conflicts occurred during the approach phase. Furthermore, another study reported that communication errors were involved in 37% of aircraft accidents [25].

1.2 Research gap and motivations

A current trend to achieve interaction quality between parties is to study the accuracy of the information transmitted [26-29]. The number of informational items transmitted in a single communication, mental workload, and prosodic features of communication have been identified as factors that affect the accuracy of information transmission [27, 29]. A system of semantic categorization has been developed to reduce the mental resources required for recipients to understand the information transmitted during the interaction [26]. At the same time, the implementation of data-link technology in the future promises to gradually reduce potential errors leading to miscommunication, which replaces the traditional voice communication [30, 31]. Therefore, in addition to studying the accuracy of information transmitted, the operator's cognitive capabilities should be a key to be considered for examining operators' actions and strategies during interactions [32-34]. In a highly distributed system, the development of holistic team cognition is critical for synergizing different parties in order to satisfy a system's changing needs and manage the uncertainties [22, 35-37]. To achieve this, the shared mental model (SMM) of a team is a critical fundamental that represents a team's shared knowledge regarding how a system works [38-40]. However, the underlying SMM inconsistency between parties, known as mental model disconnects (MMDs), can be a concern that significantly deteriorates the

quality of team interaction and team cognition formed [41, 42]. Such misaligned minds due to inconsistent subjective priorities between parties make it difficult for a team to work together with the same value regarding a system's current needs, causing frequent interaction conflicts. For example, ATCOs may expedite the landing process by issuing high-speed clearance or taking a short-cut. The instructions related to this landing process may sacrifice pilots' time for operating the aircraft, leading to possible conflicts between parties [12, 43]. In the case of landing, the possible MMDs coupled with the dynamic terminal area with limited space and time results in a system prone to errors, which lead to system breakdown that causes potential risks when not rectified in a timely manner.

To identify how an adverse event is caused, empirical examination of the causal relationship between MMDs is lacking. To satisfy this need, a closer look at the interaction mechanism of a team can be a leverage point. The initiation of interactions not only disseminates the information needed but also triggers operator SMMs to be updated and synchronized, forming the required team cognition [39, 44]. In the current work on team interaction, information dissemination in an explicit manner is mainly emphasized. However, the interaction mechanism is no longer limited to such explicit manner. Instead, the interaction can also be conducted in an implicit manner [45-47]. The implicit interaction requires one to predictively anticipate and satisfy team

members' needs by actively comprehending a system's changing state, thereby minimizing the required communication. As a matter of fact, the implicit interaction is commonly used between an experienced captain and an ATCO to achieve seamless interactions [48]. However, few studies have considered the implicit interaction in investigating team coordination. Hence, a more sophisticated interaction mechanism is needed to determine how the possible MMDs are involved in team interaction, causing unwanted performance.

In addition, a suitable methodology for implementation is crucial. Currently, qualitative analysis such as interview or database analysis is widely used to investigate a human's cognitive process [34, 42, 49, 50]. However, those methodologies are limited to study team cognition's continuous and dynamic nature. Based on the Swiss cheese model in the field of system safety, an adverse event is always caused by accumulated risks from various loopholes in a system [51, 52]. Similarly, as the team cognition is continuously evolving, the risks from the MMDs can be the loopholes that cause unwanted coordination results. However, with qualitative approaches, descriptive exploration is limited to investigation in the evolving context, which makes it challenging to clarify how various MMDs ultimately cause an adverse event. To overcome this issue, computer simulation can serve as a more powerful tool than traditional methodologies to cope with a system's uncertainties and complexity [53, 54].

Specifically, in this thesis, agent-based simulation is adopted, which can effectively address the qualitative nature with a quantitative approach. Details are further elaborated in the literature review. Accordingly, a simulation-based framework is proposed to study how various MMDs affect a team's interaction in a continuous and dynamic fashion.

Several research gaps regarding the MMDs are presented. It is worth to investigate the methods of improving the resilience and safety level in the landing stage. The research gaps are summarized as follows:

1. The mechanism of MMDs considering an adverse event lacks a systematic review.

In particular, the negative effects of various MMDs on different types of interaction (implicit and explicit interaction) and the context of interaction breakdown are worth to study and have yet to be well addressed in the literature.

2. As the team cognition changes from time to time, the risks owing to MMDs will be accumulated progressively. However, it is limited for existing methodologies to study continuous and dynamic team cognition. Therefore, the root causes of risk outcome are rarely reported. To overcome this issue, a novel framework of the methodology is proposed in this thesis.

1.3 Objectives and scope

To fill the research gaps mentioned in Section 1.2, this study aims to investigate into an unstable approach in aviation from the perspective of team interaction. By formulating a simulation-based framework, the effect of MMDs on the evolving team cognition can be determined and simulated, outlining the context of an unstable approach. Accordingly, insightful knowledge regarding the improvement in landing safety can be obtained in order to meet the future needs of the aviation industry. This thesis can be decomposed into three objectives with respective tasks that need to be achieved. Broadly, the first two objectives aim to build a theoretical framework to systematically explain how MMDs affect system performance, whereas the last objective is to further extend the knowledge obtained for improving landing systems in the future.

(1) Examine MMDs that occur and determine the corresponding context.

- Define basic characteristics and possible effects of MMDs.
- Extract and compare the SMMs between pilots and ATCOs to identify potential MMDs.
- Analyze the negative effect of the identified MMDs to explain the conflicts in both implicit and explicit interactions.
- Study the possible relation between MMDs to provide an overall picture

regarding the occurrence of an unstable approach.

- (2) Propose a simulation-based framework, that is, the framework of evolving team cognition (FETC), to explain the effect of MMDs on the evolving team cognition in a landing phase.

- Construct the relationship between MMDs, interaction patterns, and team cognition to model a team's interaction process in a complex system.
- Implement FETC to simulate the contribution of the MMDs between pilots and ATCOs to an unstable approach.
- Validate the model developed on the basis of the simulation results.
- Outline the context of an unstable approach from the perspective of MMDs to pinpoint the root causes that should be addressed.

- (3) Implement the simulation results for determining recommendations for improving landing safety in the future.

- Analyze how the major MMDs can be eliminated.
- Build a model to simulate how a landing system's reliability and efficiency are accordingly improved in the future.

To further define the work in this thesis, the following research scopes are listed to establish the boundary with respect to each objective.

- (1) This thesis aims to examine the characteristics and possible negative effects of

MMDs in a highly distributed system with heterogeneous operators. Accordingly, a system structure is a major prerequisite for this research. Implementation of the obtained results into different system structures should be considered.

- (2) The proposed simulation-based framework, called the FETC, aims to simulate the team interaction conducted and identify the key MMDs involved in an accident. Therefore, the proposed framework is a bottom-up approach that aims to achieve exploratory results.

- (3) The third objective can be treated as a pilot study for obtaining insights for future landing systems. Therefore, the study aims to unravel the approach to change the landing system positively instead of optimizing the system performance. In addition, the investigation is conducted based on Changi airport, Singapore. Relevant factors such as the airport design or practices should be considered for better generalization.

1.4 Thesis organization

Fig. 1-1 presents the roadmap of this thesis. In total, eight chapters are included, which are divided into four sections, namely, motivation & background, research fundamental, methodology & solution, and discussion & conclusion.

Fig. 1-1 Organization of thesis

Motivation and related work are discussed in Chapters 1 and 2. Chapter 1 presents the overall research background regarding the state-of-art of landing safety. Chapter 2 discusses the work related to the study of team SMM, the interaction process, and possible MMDs. Research gaps are accordingly described.

Chapter 3 formulates the fundamentals to cater to the research needs. First, the concept of role-specific SMM is presented to address the research issues of SMM in a heterogeneous system; this provides an in-depth understanding of the occurrence of MMDs. Then, FETC is accordingly developed, providing a more sophisticated mechanism to study the relationship between MMDs, interaction patterns, and team cognition formed. Specifically, computer simulation is adopted to investigate the dynamic and continuous nature of evolving team cognition. Accordingly, various means of involvement of MMDs in team coordination are determined, which helps in pinpointing the hotspots that need to be considered. Therefore, Chapters 4 and 5 emphasize these topics respectively. Based on the results obtained, Chapter 6 presents a pilot study to provide insights into the future improvements of a landing system.

Chapter 4 emphasizes on the implementation of a role-specific SMM and the context exploration of an unstable approach. This part will be conducted in a qualitative manner to provide a descriptive examination of the quality of team coordination. Then, by eliciting and mapping the potential MMDs, an overview of a team's cognition in an

unstable approach can be presented.

Chapter 5 is the core of this thesis. FETC will be accordingly implemented to model the evolving team behavior from the perspective of MMDs. The simulation results can provide the patterns of the MMDs that occur. The patterns generate insights for the improvement in landing safety in the future.

Chapter 6 is a pilot study based on the results of Chapters 4 and 5. Agent-based modeling (ABM) aims to simulate high quality of coordination with less MMDs. Both the system's reliability and efficiency are also introduced to investigate the exact benefits of MMD elimination.

Chapters 7 and 8 provide a comprehensive discussion regarding the research work accomplished in this thesis. The corresponding contributions, limitations, and future directions are listed.

2 . Literature review

This chapter provides a comprehensive review of one's decision-making from the perspective of Situation awareness (SA) and the role of shared mental models (SMMs) during the development of team cognition. The concept of mental model disconnects (MMDs) is introduced to overcome the existing gaps in examining interaction conflicts and the limitations of the current methodologies from the literature. The development of agent-based modeling (ABM) and the corresponding procedures for validation are discussed in this thesis. The ABM provides a basis for the following simulation-based research.

2.1 Situation awareness

In the domain of decision-making research, situation awareness (SA) has received increasing attention in the investigation of how an individual makes decisions in a dynamic environment [55]. The SA model includes three levels. Level 1 refers to the perception of environmental cues. Level 2 refers to the comprehension of the meaning of the cues on the basis of a corresponding mental model. Level 3 concerns projecting the current situation to anticipate future events. This cognitive process helps an individual to finalize the goals to be achieved in a dynamic environment.

According to **Fig. 2-1**, SA can be affected by two dimensions: the mental model

of a human operator, and the goals under the current scenario. First, the mental model can offer dynamic knowledge structure to comprehend meaningful patterns under dynamic knowledge structure in the current situation. Therefore, it can be a predominant basis for the quality of decision-making. The development of a mental model highly relies on both the operator's knowledge and solid experience [56]. Novices can only conduct context-free or linear rules to make the decision, which will lead to a poor decision quality under changing conditions. Experienced operators can understand the perceived cues in non-linear manners and plan for long-term goals accordingly. Regarding the goals formed, this can be deemed a guide for following decision-making [57]. The goals do not only determine the corresponding mental model needed to achieve a specific purpose but also guide the operator's attention and perception of certain categories of cues. Hence, with improper goals, the operator will be unable to realize the current situation with the correct mental model and perception of needed information, resulting in wrong decision-making. Therefore, considerable research has also identified and verified the relationship between SA and individual performance [4, 58, 59].

Fig. 2-1 How situation awareness works [18]

2.2 Interactive team cognition in a landing system

Furthermore, the concept of SA has been extended to explain how coordinative decision-making is performed by a team [36, 55]. An individual utilizes the corresponding mental model to comprehend the cues from the environment, so a team should have SMMs to work together as an individual. By definition, SMM represents a team's shared knowledge regarding how a system works [38-40]. To react to a system's changing conditions, the interaction between parties is needed to update and synchronize operators' SMMs and form the required team cognition [22, 44, 60]. The process is particularly critical for a multi-team system (MTS), which enables heterogeneous stakeholders to comprehend the environmental changes with a consistent value. However, in a landing system, the following challenges pertaining to holistic team cognition should be considered: (1) a highly distributed system, (2)

unequal information sharing, and (3) high workload and possible emotions involved.

1. Highly distributed system: For a modern complex system, heterogeneous parties aim to accomplish various goals to satisfy the required productivity, which emphasizes the necessity of effective team coordination [61, 62]. However, in a system that requires highly trained and experienced operators, such as in the aviation industry, the heterogeneity of the parties is particularly significant, making it challenging for all team members to achieve aligned priorities regarding system operation [12, 63]. Furthermore, inconsistent subjective priorities may accidentally affect a team member's performance.

2. Unequal information sharing: Due to the inevitable difference in goals, as mentioned above, the implementation of an information system between parties also varies. The possible information gaps make it difficult for the stakeholders to share information regarding safety, productivity, and capacity requirements and their tradeoffs, thereby impeding the quality of coordination [12, 64-66]. For example, air traffic controllers (ATCOs) use radar maps to check the overall air traffic flow, and pilots mainly use the instruments in the cockpit to monitor the aircraft's state—these are exceedingly different areas of concern. Hence, in the dynamic aeronautical environment, the need for extra information dissemination is intense in order to eliminate the information gaps caused.

3. High workload and possible emotions involved: As aforementioned, for an aircraft in the terminal area, limited space and time lead to the necessity of frequent changes in the flight state [3, 4]. Such high workload coupled with the challenges mentioned in the previous two points may negatively affect an individual's affective state. Relevant research indicated that operators' performance or intrateam interaction is subject to the current affective state [12, 23, 67]. Relevant research also documented that the emotions associated with the ATCO's instructions make pilots feel uncomfortable. Once such a "blame mode" has been raised, the focus of communication turns into retribution instead of cooperation [23]. This not only increases pilots' stress but also eliminates opportunities to detect possible errors during interactions.

In sum, team cognition plays critical roles in integrating all of the operators' activities in a complex system. However, the issues identified above are challenges that need to be overcome. In general, such heterogeneous subjective priorities or information gaps among operators are particularly common for an MTS, which emphasizes the importance of high-quality team interactions. However, achieving this becomes increasingly difficult with the intensive workload and the limitation of communication instruments. Accordingly, frequent interaction breakdown between parties is expected, making a system prone to errors. Therefore, to achieve seamless

interactions for a team to rapidly react to a dynamic environment, the possible breakdown in the development of team cognition is a critical issue to be examined.

2.3 SMMs and MMDs

Achieving a consistent SMM among the operators is fundamental for forming holistic team cognition in complex systems such as the aviation or medical care industry [23, 68]. Basically, two types of SMMs have been identified [38, 69]: task-related and team-related.

1. The **task-related SMM** can be divided into two categories: (1) technology and equipment and (2) tasks or jobs. First, the task-related SMM of technology and equipment means the shared knowledge that enables the team to understand the technology they are interacting with, such as equipment functions and the system limitation. By contrast, the SMM of tasks or jobs represents the shared knowledge that describes how the tasks and procedures are executed as well as the probable contingency. This shared knowledge is particularly important for one to perform the tasks without conflicting team member requirements.
2. The **team-related SMM** represents the shared knowledge about how the team members interact with one another. Relevant dimensions include (1) the course of action, (2) items of information to be transferred, and (3) team spirit. The first dimension, the course of action, refers to the strategies or actions conducted during

communication for coordinating each other's requirements. Then, the second dimension determines whether a team can exchange critical items of information. Unnecessary information, known as "noise information," can cost extra mental resource for operators to make decisions [4, 70]. Lastly, the third dimension refers to the atmosphere, attitude, or even climate of communication. Poor team spirit may cause a negative emotion or even quarrel, deteriorating the efficiency of interactions [23]. With the proper team-related SMM, various team members are able to initiate literal communication to coordinate each other's requirements.

By contrast, a faulty SMM, which entails MMDs, can cause interaction conflicts and defective team cognition. MMDs can be described as the disagreement between the SMMs of various individuals. The following three categories of MMDs have been identified [41, 71]:

- *Informational disconnects* occur when the information shared among operators varies. The information gaps make it difficult for a team to perceive environmental changes in the same manner.
- *Evaluative disconnects* occur when various operators perform different evaluations using the same available information.
- *Operational disconnects* occur when one party executes actions that are not in accordance with the expectations of another party.

Furthermore, the causal relationship among MMDs can provide some further insights. It is reported that operational disconnects can be caused by the informational and evaluative disconnects [41, 71]. Meanwhile, the informational disconnects can cause evaluative disconnects as well as operational disconnects. In sum, the negative effects of possible informational and evaluative disconnects are relatively implicit. The information gaps and inconsistent evaluative criteria can only increase the possibility of occurrence of operational disconnects. While an operational disconnect can be deemed as the one posing direct threats to the quality of system performance, it requires a team to take additional actions to coordinate the respective requirements. The idea is depicted in **Fig. 2-2**. The labels (A, B, C, and D) mentioned for each of the disconnects refer to the party responsible for the disconnect in the system. The sum of disconnects occurring during interactions characterizes the team cognition formed and corresponding system performance.

Fig. 2-2 Relationship between MMDs and system performance

In brief, the consistency of SMM is fundamental for a team to conduct proper interaction. However, limited research systematically investigates the negative effect of MMDs. Specifically, the MMDs under different categories of SMMs (task- and team-related) are expected to affect the quality of team interaction in different manners. Under the task-related SMM, MMDs cause stakeholders to be unable to understand how their team members execute their tasks or their strategies for doing so. Consequently, operators may execute their tasks in a fashion that affects team members' requirements. By contrast, the MMDs under the team-related SMM cause difficulty in coordinating each other's requirements and communicating critical information during the interaction. Furthermore, how various MMDs jointly contribute to defective team cognition remains unclear.

In sum, in a distributed system, inconsistent SMMs jeopardize the interaction of heterogeneous agents in achieving a common goal. The possible causal relationship among informational, evaluative, and operational disconnects helps to investigate the unexpected operations that occur during team interactions. The MMDs under task- and team-related SMMs also may cause unsatisfactory interaction in different manners. Furthermore, the interactive process between different categories of MMDs should be considered to uncover the context of the interaction conflicts that occur in an accident. However, systematical examinations of these issues are limited in the literature.

2.4 Implicit and explicit interactions

To form the required team cognition, interactions are required to synchronize SMMs between parties, which can be achieved in both implicit and explicit manners [45, 47]. Implicit interaction is based on individuals' anticipation regarding a system's changing conditions, which enables the individuals to adjust their own performance to support team members without communication or plan. To achieve this, an individual must actively monitor the current system state to understand team members' changing needs. Conversely, explicit interaction denotes the literal communication that intentionally coordinates the respective requirements. This purposeful interaction emphasizes the urgency for a team to mitigate potential errors in a timely manner.

In fact, the roles implicit and explicit interactions play are subject to the structure of an MTS [46, 61]. The idea is illustrated in **Fig. 2-3**. In general, the implementation of both implicit and explicit interactions is available for most of the teams having respective goals, known as the between-component teams. However, for the team having common goals, known as the within-component team, implementation of both interactions is not necessary. For example, the pilots in a cockpit can be treated as a within-component team with a common goal: executing a safe landing. The multi-directional workflow enables operators to coordinate simultaneously [72]. Therefore, the demands of information dissemination and integration in explicit interaction are

emphasized for purposeful coordination. As for the landing system, the combination of pilots and ATCOs constitutes a between-component team. Pilots and ATCOs are the two major parties involved with the respective goals. Specifically, pilots are responsible for maneuvering the aircraft and achieving a proper landing, while, pilots' operations are always subject to ATCOs' instructions based on air traffic flow management. The reciprocal interaction enables the between-component team to frequently adjust their respective performance and coordinate in an iterative manner [73]. The mutual information shared in a team creates opportunities to conduct implicit coordination. Furthermore, explicit communication is expected to align the actions conducted. Therefore, a mix of both implicit and explicit interactions is expected.

Fig. 2-3 Team structure in a landing system

Fig. 2-4 SMM and team interactions

To achieve high-quality implicit and explicit interactions, the quality of the SMM is vital. Specifically, research has identified the respective role that different SMMs play during different interactions [42, 45]. The idea is presented in **Fig. 2-4**. First, the task-related SMM refers to the shared knowledge of how the system performs, including task procedures, constraints, and strategies, which satisfies the need for anticipating team members' course of actions in an implicit manner. This predictive adaption can also reduce the necessity of conducting literal communication [47]. By contrast, the team-related SMM represents shared knowledge of the required interaction pattern, strategies, information delivery, or even team spirit. It enables a team to initiate purposeful communication with the required information in a timely manner.

In brief, considering both implicit and explicit interactions provides a leverage point to closely examine both task- and team-related SMMs to contribute to the quality of team coordination. In a landing system, although the execution of implicit interaction

is not well regulated, it is still implemented by experienced operators to improve a system's sensitivity to react to changing conditions [48]. As for the explicit interaction, it is mostly executed with regulated routines. However, under contingent scenarios, non-routine communication is especially critical to coordinate each others' requirements, ensuring the system's reliability [28]. Accordingly, the combination of both implicit and explicit interactions characterizes how a landing system operates. Furthermore, it helps to examine various MMDs in a systematic manner.

In sum, both implicit and explicit interactions play a critical role in an MTS. The interactive process between implicit and explicit interactions determines whether a team is able to determine proper team cognition to conduct the required performance. To achieve this, identifying proper SMMs between parties is fundamental. The underlying MMDs may cause various interaction conflicts, leading to defective team cognition. However, little research outlines a comprehensive framework to explain such a contextual relationship.

2.5 Existing methodologies for examining SMM

To measure the quality of SMM and underlying inconsistency, relevant methodologies have been widely discussed [40, 50, 74]. In general, these methodologies share a similar fundamental, regarded as SMM similarity. Generally speaking, the higher similarity of the SMM reflects a greater SMM quality. This is

because the similarity of SMMs enables all the operators to treat the environmental changes with consistent value and reduce possible conflicts due to MMDs. Three categories of methodologies are widely adopted: SMM matrixes, structure presentation, and process tracing. Details are provided in **Table 2-1**.

First of all, from the perspective of the SMM similarity examination, the SMM matrix is the most widely used approach. A matrix is constructed on the basis of the critical shared knowledge related to system performance. Then, participants are required to rate the relation between each pair of knowledge to finish the matrix. Participants' matrixes can be compared to identify the breaches in the SMM accordingly. As for the second approach, structure presentation aims to determine the method of organizing a team's SMM. In general, concept mapping or pathfinder are common methodologies to be used. The relationship among concepts of SMM is elicited and compared for examining the SMM similarity. Process tracing takes a relatively different perspective to examine a team's SMM and explore a team's SMMs dynamically by tracing the cognitive flow during team coordination. To sum up, most current methodologies place emphasis on the similarity of intrateam SMMs, while the process tracing adopts a more explorative examination.

However, owing to the following two major reasons, these methods are limited to address the nature and possible defects of SMMs in a heterogeneous system. Firstly,

these methods are unable to fully identify the SMM breakdown caused by the inevitable goal difference or an insufficient understanding of the system goals. In a heterogeneous team, the distributed goals and the requirements of specific expertise may cause inconsistency in intrateam SMMs [50]. In fact, the heterogeneous subjective priorities between parties are common for a system to achieve various required sub-goals. Consequently, it is difficult for a researcher to pinpoint the critical breakdown for elimination. Secondly, the contextual relationship among the identified SMM breakdown cannot be accurately identified by the existing methodologies. As relevant research states, the different types of MMDs (informational, evaluative, and operational disconnects) have a certain causal relationship [41, 71]. Such qualitative connection facilitates a more comprehensive understanding regarding the interaction conflicts. However, with the current methodologies, using quantitative-based approaches, such as the SMM matrix or conceptual model, only the items of SMM breakdown can be identified but the underlying connection cannot be clarified. On the other hand, using more qualitative-based approaches, such as process tracing or concept mapping, without implementing quantitative examination, it is difficult to verify and generalize the results obtained for effective accident prevention.

Table 2-1 Current methodologies for SMM examination

Fundamental	Literature	Elicitation method
SMM matrixes	Stout <i>et al.</i> (1995) [75]	Develop a matrix to study intrateam similarity.
	Mathieu <i>et al.</i> (2000) [38]	Develop shared-knowledge matrix to examine knowledge similarity of a team.
	Smith-Jackson <i>et al.</i> (2007) [76]	Examine priority ranking among parties.
	Smith-Jentsch <i>et al.</i> (2008) [77]	Develop an importance-ranking matrix to study how team members treat critical knowledge regarding system performance.
	Resick <i>et al.</i> (2010) [78]	Combine three categories of matrixes (structural network, importance ranking, and priority ranking) to measure the SMM's similarity and quality.
	Canonne <i>et al.</i> (2016) [79]	Adopt a modified "card-sorting" technique to test SMM similarity.
	Zoogah <i>et al.</i> (2015) [80]	Conduct an importance ranking of shared knowledge regarding system performance.
	Berggren <i>et al.</i> (2017) [81]	Examine priority ranking from respective operators by using MANOVA.
Structure presentation	Lim <i>et al.</i> (2004) [82]	Apply concept mapping and content analysis to study SMM consistency.
	Jackson <i>et al.</i> (2008) [83]	Apply individually constructed mental model (ICMM) to develop and compare an individual's concept mapping regarding system performance.
	Jonassen <i>et al.</i> (2013) [84]	Apply concept mapping to study SMM consistency and the relation among concepts.
	Lim <i>et al.</i> (2006) [85]	Utilize Pathfinder to test SMM

		similarity. Furthermore, examine the overall SMM of a team to test the accuracy.
	Edwards <i>et al.</i> (2006) [86]	Utilize Pathfinder to test SMM similarity and accuracy.
	Evans <i>et al.</i> (2012) [87]	Test the similarity of the proposed mental models of integrated care (MMIC). Three types of mental models are included—integration task, system role, and integration belief.
Process tracing	Van Someren <i>et al.</i> (1994) [88]	Apply the think-aloud method to dynamically trace how operators coordinate.
	Santos <i>et al.</i> (2016) [89]	Trace the similarity and accuracy of a team's temporal mental model in a simulation.
	McNeese <i>et al.</i> (2017) [90]	Study and trace the development of agreement by providing a scenario for a team to coordinate.
	Gray <i>et al.</i> (2017) [91]	Succeeding research of McNeese <i>et al.</i> (2017) [90].

In a nutshell, although SMM measurement has received extensive attention, few studies have conducted an in-depth examination of the issues of a heterogeneous system. In this case, instead of aiming for highly similar SMMs for team members, it is more effective for them to possess “role-specific” SMMs, which would enable them to actively cope with the heterogeneity and achieve seamless coordination. In addition, it is vital to examine the contextual relationship among the SMM breakdowns in order to pinpoint the root causes that must be mitigated. Accordingly, a new perspective to approach SMMs and a modified methodology are warranted for satisfying the

abovementioned requirements.

2.6 Agent-based modeling (ABM)

In the domain of system safety, it is well accepted that an accident is always caused by the accumulation of system errors from loopholes in various aspects of a system [51, 52]. Therefore, a more comprehensive examination of accident occurrence in such an evolving context is vital. From the perspective of team cognition, the risks from MMDs during interactions can be the loopholes. As a team's cognition evolve in response to changing conditions, the risks from MMDs also accumulate progressively, which causes adverse events. To examine the continuous and evolving nature of accidents in a complex system, computer simulation can be advantageous. In general, three approaches are commonly adopted: discrete event simulation (DES), system dynamics (SD), and ABM [92, 93]. The selection of the technique depends on the characteristics of the work. Specifically, SD emphasizes on macro-level simulation, which aims to study the effect of aggregated factors. How a policy or climate change affects people is an example. DES aims to achieve a micro-level examination and is commonly used to study the workflow or even decision-making. In this thesis, how various MMDs connect and contribute to an adverse event is the focus. To achieve this requirement, both micro- and macro-levels of examination must be considered. Therefore, ABM is

a suitable approach [94, 95]. In general, ABM is a bottom-up approach (micro-level) that simulates how autonomous agents act according to their own rules or interests. The interactions among agents characterize the emerging system performance (macro-level) [96]. Furthermore, ABM is a flexible approach, with no regular rules for its development; therefore, different methods of simulation can be combined to meet the research needs [97].

Specifically, ABM is suitable to study the qualitative nature of MMDs by using a quantitative approach. The flexibility allows the implementation of the formative theory in ABM [98]. The concept of SA is applied to study an individual's cognitive process in a team [54, 99, 100]. Furthermore, relevant research in recent years introduced SMMs into ABM. The contribution of the aggregated SMM is mainly studied, which considers the characteristics of SD into ABM. Agents' actions are modeled on the basis of the aggregated quality of SMMs, which uncovers the corresponding changes in the interaction pattern among agents [101, 102]. In general, these studies provide insights regarding the overall benefits of high-quality SMMs. However, from the perspective of accident analysis, they do not identify the root causes of interaction conflicts occurred by examining aggregated SMMs.

From the system perspective, it is well accepted that an accident occurs by the accumulation of system errors from loopholes in various aspects of a system [51].

Similarly, system risks emerging from defective team cognition may also accumulate progressively, which is illustrated in **Fig. 2-5**. In the right figure, white circles denote the actions conducted during interactions and black circles represent the underlying MMDs. A team should adapt to changing conditions and time progression to detect and correct the risks in a timely manner. Otherwise, the accumulation of risks may evolve to accidents. An unstable approach in commercial aviation is one of the cases where the team may miss the window to address the risks developed because of which the pilots face difficulty in mitigating the deviated landing profile [9, 43]. Accordingly, the underlying operational disconnects can be treated as the loopholes during an interaction. For effective accident prevention, the identification of key MMDs in the evolving context of adverse events is critical.

In sum, ABM is a flexible approach to studying the emerging system performance (macro-level) from the perspective of agents' actions and interactions (micro-level). Where necessary, ABM can also combine other methods of simulation, such as SD or DES, to satisfy the research needs. Furthermore, by introducing formative theory into ABM, a more predictive simulation can be achieved for studying reality. The combination of these advantages makes ABM a suitable approach. However, few studies utilize the importance of SMMs by introducing the concept of MMDs to investigate evolving team cognition in an accident.

Fig. 2-5 MMDs in the evolving context of accidents

2.7 Validation and verification for simulation research

For simulation-based research, verification procedures are essential to ensure the fitness of the model corresponding to the conceptual model [103, 104]. In the cases of ABM, most ABMs involve multiple levels of system structure and complex interaction among agents. Therefore, an ABM's robustness should be verified and validated via examining the effects of different parameters on the outcomes. In general, a robust ABM should not be subject to the change of a single parameter. Thus, a model should be affected by

a dominant parameter reasonably and predictably. Therefore, the sensitivity test that comprises three different categories is adopted, including: 1. one-factor-at-a-time (OFAT); 2. model-based output variance decomposition; and 3. model-free output variance decomposition [105].

1. OFAT can investigate the relationship between simulation output and the effects of a changed parameter. The outcome of the normal setting is generated as a baseline. Then, by changing one parameter and fixing all the other parameters, the model will examine the changes in output. In general, OFAT is good at examining an ABM's emergent pattern and robustness, but it lacks the consideration of interaction among parameters or agents.
2. Model-based output variance decomposition aims to decompose the variance of simulation output via regression analysis. By fitting a regression function to the simulation outcomes, the variance of the outcomes can be obtained. Accordingly, the sensitivity of a parameter can be examined by checking the proportion of the variance of the parameters. The variance obtained can discover the output changed caused by a single parameter and interaction among parameters, which also ensure the examination of an ABM emergent pattern and robustness. However, a good fit between the regression model and the ABM developed is a prerequisite.
3. Model-free output variance decomposition does not require regression functions

to decompose the variance. The expectation value of the model is calculated by fixing the parameter to be tested and varying all the other parameters, and compare with the baseline. Then, the variance can be computed over all the possible values of the parameter in the testing environment. The larger variance implies a higher sensitivity of the parameter. This approach only considers the averaged effect of a parameter causes. Thus, it is limited to explain possible emergent behavior and robustness.

After verifying the mechanism of the system, validation procedures are required. Empirical data has to be collected to examine whether the simulation output can reflect the real situation. [102, 106]. Owing to the fact that an unstable approach is hard to capture in an actual environment, conducting traditional approaches for verification is challenging. In field observations, it is difficult to observe a highly trained operator make mistakes, especially for the event with extremely low probability. Moreover, the voluntary reporting system is limited in its ability to record cognitive errors. In order to overcome these issues, current research has provided insights by considering the similarity of causation [107, 108]. The causal structure of simulation and the real-world can be elicited and compared. A good model fit can, therefore, support the ABM developed in an empirical manner, which is suitable for examining the context of an adverse event.

2.8 Summary

Based on the discussion above, the research gaps stated in Section 1.2 can be further elaborated as below, emphasizing on the issues that need to be addressed.

- (1) **Examination of MMDs during interaction:** Interaction is a key phase for stakeholders to synchronize their respective SMMs in order to achieve more holistic team cognition. Specifically, both implicit and explicit interactions are vital, which involve task- and team-related SMMs. However, the negative effect of MMDs on the results of interaction has yet to be clarified. Furthermore, how these underlying MMDs jointly cause an adverse event, an unstable approach in this case, also lacks systematic examination.
- (2) **Development of an ABM framework:** The cognitive process described above is normally investigated in qualitative and descriptive manners. Corresponding verification is insufficient to identify the key MMDs that must be addressed for effective accident prevention. Based on the Swiss cheese model, an adverse event is caused by the accumulation of system errors due to loopholes in various aspects of a system. A team should interact and adapt to changing conditions and time progression to detect and correct the risks in a timely manner. However, the underlying MMDs prevent a team from doing so, causing system errors to evolve. To address this issue, a framework is needed to systematically model the

contextual relationship between MMDs and adverse events.

3 . Research fundamentals

This chapter examines the fundamental issues related to building a systematic framework used to determine the causal relationship between underlying mental model disconnects (MMDs) and adverse events. The steps that involve in building the framework include a definition of role-specific shared mental models (SMMs), determination of underlying MMDs, the involvement of MMDs in team interactions, and implementation of ABM simulation. Accordingly, a simulation-based framework, called the framework of evolving team cognition (FETC), is proposed to study how MMDs affect the dynamic scenarios and contribute to evolving team cognition. Using this framework, the context of an adverse event can be elucidated, thereby achieving a more comprehensive accident analysis. Furthermore, the technical framework is presented for a more comprehensive explanation of FETC implementation.

3.1 Role-specific SMMs

In this section, the role-specific SMM is introduced to provide a more comprehensive understanding of the contribution of SMMs in a heterogeneous team. Furthermore, the corresponding approach of determining underlying MMDs is discussed.

3.1.1. Definition of role-specific SMMs

Based on the explanation in Section 2.4, the quality of intrateam SMMs is determined by the SMM similarity among team members. Consistent SMMs facilitate holistic team cognition, enabling all the parties to have common goals. However, as mentioned, in an MTS, especially for a system comprising highly trained operators, different subjective priorities commonly exist and are inevitable. Therefore, the contribution of intrateam SMMs should be examined from a different perspective. Specifically, how a team overcomes such heterogeneity and the underlying challenges should be the major focus.

To study how a heterogeneous team works together, the role-specific SMM is defined in this thesis, which can be approached using the concept of system coordinability; that is, for a system with different units, each of the parties can have at least one solution to solve a mutual problem [109, 110]. With this, operators having protracted experience can act in ways corresponding to team members' intention by conducting mutual mental simulation [111, 112]. In this case, the function of an SMM can be decomposed into two aspects. First, the mutual problem can be the common goal determined by a team, which is based on team cognition formed on the basis of the synchronized SMMs between parties. In this case, the development of common problem during interactions can be explained by the original definition of the SMM,

which emphasizes the similarity of SMMs. Specifically, a team has to determine “proper and consistent” common goals, which requires all the stakeholders to comprehend the current environment in the same manner. Improper common goals result in the failure of a team to react to a system’s current condition with the correct course of actions, whereas inconsistent common goals increase the difficulty for the team members in coordinating respective requirements. Second, the solution provided by each of the parties should be compatible with satisfying the common goals that are determined; this is challenging to achieve seamless coordination. An operator must be capable of deducting team members’ expectations and provide at least one “acceptable” solution. The solutions that do not match team members’ expectations will cause possible conflicts, impeding the accomplishment of common goals. Therefore, ideally, determination of proper and consistent common goals and provision of acceptable solutions should both be such that proper coordination is achieved.

As discussed above, the determination of proper and consistent common goals relies on the SMM similarity as the original version defined for the heterogeneous parties to comprehend the environment in a consistent manner. By contrast, as for searching acceptable solutions for achieving mutual goals, the relationship between individual performance and team members’ expectations must be considered, which is subject to the roles a party plays. Therefore, compared with the original definition of

SMM, which emphasizes on the similarity, the role-specific SMM focuses on examining compatibility. Herein, the role-specific SMM can be defined as the knowledge required for a party to provide at least one acceptable solution for satisfying team members' expectations based on proper and consistent common goals.

Fig. 3-1 Role-specific SMMs for team coordination

The idea is illustrated in **Fig. 3-1**. The ideal model of the role-specific SMM is presented in **Fig. 3-1 (a)**. Specifically, the role-specific SMM is supposed to cover the original SMM for understanding how team members treat their common goals. It should also be part of an individual mental model for searching acceptable solutions. Furthermore, the composition of a model is subject to changing conditions. Considering contingent scenarios, as an example, a team may face difficulty in defining consistent and proper goals, let alone searching solutions for satisfying team member's

expectations. Two examples are presented in **Fig. 3-1 (b)** and **(c)** for a clearer demonstration. In these two cases, the team members' model of role-specific SMMs is set to be ideal. First, for ideal coordination, proper and consistent common goals are determined by synchronized SMMs. Then, the role-specific SMM helps to deduct team members' expectations from overlapping SMMs, and determine acceptable solutions from the individual mental model. By contrast, for the scenarios prone to conflicts, the role-specific SMM does not cover the synchronized SMMs. As a result, it is difficult to meet team members' expectations, leading to actions that are different from team members' expectations. In real-life scenarios, the individual's model of the role-specific SMM is not ideal in every circumstance. To achieve satisfactory coordination, one's role-specific SMMs should at least cover the range where the original SMMs overlap and enables one to conduct minimum actions to satisfy the common goals between parties.

In sum, although the similarity of SMMs plays a critical role for a team to achieve required common goals, the contribution of SMMs should be considered in a role-specific manner to achieve a more empirical examination. Thus, the concept of role-specific SMMs is proposed and defined. It can be a leverage point to study how heterogeneous stakeholders in an MTS accomplish required team coordination and how possible interaction conflicts are caused.

3.1.2. Determination of MMDs

With the inclusion of the proposed role-specific SMM, the breakdown in SMMs should also be redefined. In this thesis, the compatibility between heterogeneous parties is set to be the key to determining underlying MMDs. Based on the previous section, the composition of the role-specific SMM is subject to changing conditions, causing different patterns and results of coordination. Thus, the examination of the role-specific SMM is scenario-driven. The relevant scenarios a team may undergo should be described to study the relationship among common goals that need to be achieved, team expectations, and corresponding solutions. Then, by comparing the role-specific SMMs of different parties, possible MMDs can be determined to examine the breakdown that needs to be addressed in an MTS. The flow is presented in **Fig. 3-2**.

Fig. 3-2 Determining MMDs in role-specific SMMs

In scenario N, each operator has the respective role-specific SMMs, aiming to satisfy team members' expectations. Simultaneously, an operator also has corresponding expectations regarding current goals. By comparing the role-specific SMMs of the operators, three items can be identified: operator A's role-specific MMDs, operator B's role-specific MMDs, and conflicting MMDs. Operators' role-specific MMDs are identified when one is unable to provide acceptable solutions that satisfy team members' expectations. Conflicting MMDs are identified when both parties' expectations contradict, reflecting that heterogeneous operators could not form proper and consistent common goals for the current state. The consequences are similar to the original SMM. SMM breakdown makes it difficult for a team to comprehend the environment in a consistent manner, causing defective team cognition. In general, among all the MMDs, operational disconnects will be the first to be found. Then, through retrospective examination, we can identify the underlying informational and evaluative disconnects. Furthermore, as defined, two categories of SMMs are identified: task-related and team-related SMMs [38, 69]. Accordingly, the MMDs under the two types of SMMs should negatively affect team coordination in different manners, which is elaborated in the subsequent section.

In sum, the examination of role-specific SMMs is scenario-based, which aims to study the relationship between common goals, expectations, and solutions provided.

The misalignment between a party's decision and team members' expectations can cause MMDs, deteriorating the results of coordination. Furthermore, contradicting expectations can cause inconsistent goals between parties, leading to failure of a system to function as desired.

3.2 Role-specific SMMs in implicit and explicit interactions

For a team to form the required team cognition, the execution of interaction is compulsory. In general, operators' mental state will be updated and synchronized for conducting the proper course of actions [22, 44]. As mentioned, it can be achieved both implicitly and explicitly [45, 47]. As shown in **Fig. 2-4**, implicit interaction relies on task-related SMMs, whereas explicit interaction depends on team-related SMMs. Accordingly, the MMDs under both SMM types can cause different consequences during the interaction. The MMDs under task-related SMMs can be an onset of interaction conflicts. Due to the ignorance of team members' limitation and strategies, a party cannot actively satisfy team members' expectations. What is worse, team members' needs or resource may be sacrificed. For example, high-speed clearance issued by ATCOs may reduce pilots' time available for operating the aircraft [12]. In the MMDs under the team-related SMM, one may not be able to take required actions

or provide expected information, impeding purposeful coordination in the team. Furthermore, the team may miss the window for preventing system errors in a timely manner. In this case, pilots' over-confidence can be a cause for initiating late interaction, leading to late go-around [113]. Furthermore, the possible issues of team spirit in team-related SMMs also trigger operators' emotion during the communication, leading to quarrels [23].

Fig. 3-3 Implicit and explicit interactions in team cognition

By including both implicit and explicit interactions in the development of team cognition, a conceptual model can be presented to display a rotation of interactions conducted, which is illustrated in **Fig. 3-3**. A team will keep interacting with each other

iteratively until a consensus is reached. The consensus determines the formation of team cognition and the ways a team performs. Changes in the system state may cause the evolution of current scenarios, triggering a new rotation of interactions. This model also helps to elucidate the negative effects of MMDs. The possible interactive process among MMDs is demonstrated.

From the perspective of role-specific SMMs, different operators have respective MMDs regarding the characteristics of their own tasks. Therefore, each of the operators' MMDs should be taken into consideration separately. As for examining the connection between MMDs, two concepts are considered. First, the identification of operational disconnects is critical. Among the three categories of MMDs, operational disconnects are those that pose direct threats to the quality of team coordination. By identifying them, we can locate the hotspots to be considered and enact corresponding interventions. Second, the unwanted results of interaction are the combination of operational disconnects that occur. Based on the perspective of system safety, a well-performed team is able to intercept the potential risks promptly [32]. One party's MMDs should be detected and mitigated by their team members. However, team members' operational disconnects may worsen the negative effect caused by the previous operational disconnects, thereby jointly causing faulty interaction results. Consequently, unsatisfactory interaction results lead to defective team cognition.

To conclude, the conceptual model provides a comprehensive overview of the contextual relationship among MMDs under task- and team-related SMMs, interaction patterns (implicit and explicit), and team cognition. Accordingly, one can clarify the involvement of MMDs and locate the key issues to be considered during team coordination.

3.3 Development of FETC

With the role-specific SMM defined and the conceptual model proposed as shown in **Fig. 3-3**, a clearer picture regarding interactive team cognition is expected. To simulate such a qualitative nature in a longitudinal manner, flexible ABM is a suitable approach. Accordingly, a simulation-based framework, called the FETC, is proposed in **Fig. 3-4**. The agents in ABM refer to the autonomous entities with their own rules and interests. Thus, a team can be treated as an autonomous agent, while team cognition forms the rule for the agent to act upon. To achieve this, the interaction process is modeled as algorithms to dynamically determine suitable rules for reacting to the current condition (Scenario N). Nevertheless, the connection among various MMDs leads to varying results of team cognition (N_a – N_n), leading to different actions conducted. To apply the conceptual model into ABM development, some aspects must be examined.

Fig. 3-4 Framework of evolving team cognition (FETC)

1. **Scenario determination:** To develop an agent-based model based on the concept of FETC, the possible scenarios in the event should be identified. In this work, a scenario can be defined as the correspondence between the system state and environmental changes. From the perspective of landing stability, the system state can be set as the aircraft's landing profile. An aircraft with a deviated landing profile (airspeed and altitude) and insufficient track miles denote a scenario prone to an unstable approach. Thus, the interaction conducted should be in response to the requirements emerged in this scenario. In addition, the system state is also subject to sudden changes in environment, which generate completely different requirements. Therefore, the correspondence between the system state and environmental changes should also be carefully examined. Unexpected weather conditions and runway changes are some of the adverse scenarios in a landing system.

2. **Agent logic modeling:** In FETC, a team's interaction process is modeled as algorithms to calculate team cognition required in response to scenarios. As discussed in Section 2.2, interaction patterns are subject to the team structure. For a between-component team, both implicit and explicit interactions are considered. A team's interaction process can be accordingly developed by determining the relationship among MMDs. As presented in **Fig. 3-4**, the inclusion of MMDs can result in various kinds of team cognition in response to a scenario, determining the courses of action that must be taken to update the system state. In general, different scenarios may require different interaction patterns. To simplify the complexity of the interaction pattern, routine and non-routine interactions can be considered. An exploded view of FETC is illustrated in **Fig. 3-5**. For routine interaction, a general algorithm can be established to model the repetitive interaction process. With a progressing timeline, the conditional probability of MMDs can be accordingly adjusted, which simulates a team's adaptability. By contrast, the non-routine interaction is intended to respond to contingencies. Sudden changes in the environment may result in completely different requirements. Thus, a new algorithm for the interaction should be accordingly developed. Ultimately, accidents may occur when the final system state fails to satisfy system requirements.

In short, in order to examine the interactive process between updated team cognition and evolving scenarios, a simulation-based framework, called the FETC, is proposed. It aims to simulate how team cognition is formed in the event of an accident in a longitudinal manner. Accordingly, we can obtain a clearer picture regarding the involvement of MMDs, which helps in identifying the root causes of accidents that must be eliminated for better accident prevention.

Fig. 3-5 Exploded view of FETC

3.4 Technical framework and potential challenges

In this section, a technical framework is presented for a better understanding of implementation. Furthermore, potential challenges and corresponding strategies are

elaborated to overcome some possible issues.

3.4.1. Technical framework

To achieve rigorous development of FETC to simulate a team's evolving team cognition, a technical framework is presented in **Fig. 3-6**. In a nutshell, FETC is a simulation-based approach, aiming to study the qualitative nature of team cognition in an accident. First, qualitative examination and corresponding analysis are conducted to examine an accident that occurs from the perspective of MMDs during team coordination. Then, the contextual relationship among MMDs serves as a foundation for modeling how an agent, which is the team in the landing system, reacts and adapts to the changing conditions in a longitudinal manner.

Fig. 3-6 Technical framework of FETC

3.4.1.1 Context of team cognition

This part aims to explore an accident's context comprehensively and qualitatively.

In this section, four processes are presented: exploring the accident context, determining the role-specific SMMs, determining MMDs, and MMD mapping.

- 1. Exploring the accident context:** To explore the context of an accident, the database of the report system is commonly analyzed, particularly for the aviation industry [10, 114, 115]. However, a team's cognitive process is the fundamental of this thesis, which cannot be properly recorded and communicated. The critical decision method (CDM) is an interview-based methodology commonly used to examine challenging events and acquire relevant knowledge [116-118]. In general, the CDM consists of four parts, namely incident identification, timeline construction, deepening probes, and "what if" queries. The CDM is used to rebuild the context of an event, which is especially suitable for this research. In addition, the flexibility of the CDM enables operators to customize to research needs by modifying the deepening probes. Accordingly, a semi-structured interview based on the CDM should be developed to achieve a comprehensive exploration. Furthermore, to achieve smoother ABM in the subsequent step, each decision made should be investigated in as much detail as possible. Relevant items include a party's SA (perceived cues, mental model, and corresponding prediction), role-

specific SMMs, the determined common goals, and the course of actions taken (including exact parameters).

2. **Determining role-specific SMMs:** After identifying each of the decisions made by a team, role-specific SMMs of respective parties should be examined to clarify the context of coordination. The overall structure is illustrated in **Fig. 3-2**. In general, during the semi-structured interview, participants, who are pilots and ATCOs in this thesis, have to explain how they provide acceptable solutions that match team members' requirements in both implicit and explicit manners. Simultaneously, participants are also required to provide their expectations regarding a team member's performance. To analyze the interview content, content analysis is conducted to generate meaningful themes [119].
3. **Determining MMDs:** Based on the results of the content analysis, the themes can explain each party's role-specific SMM in an accident. If the party cannot accordingly satisfy team members' expectations, MMDs are identified. Furthermore, if a team member's expectations contradict with the solution provided, conflicting disconnects are generated, which impede synchronization of the team's common goal. Once the items of MMDs are determined, corresponding taxonomy is performed to categorize the categories of SMMs (task- and team-related) and MMDs (informational, evaluative, and operational); this is a

prerequisite for the subsequent MMD mapping process.

4. **MMDs mapping:** With the clarification of the characteristics of each MMD, the context of team cognition can be accordingly developed on the basis of the model presented in **Fig. 3-3**. The MMDs in task-related SMMs can jointly contribute to unwanted implicit interaction; similarly, the MMDs in team-related SMMs contribute to explicit interaction. By combining the results of both implicit and explicit interactions, the development of faulty team cognition can be identified to examine how a defective decision is made.

3.4.1.2 ABM development

In this section, ABM is performed on the basis of the context of team cognition. The following data collection, verification, and validation are conducted for a more realistic result:

1. **ABM:** As presented in Section 3.3, in this thesis, a team is treated as an autonomous agent. The mechanism for the team to determine a suitable rule for the corresponding scenario is based on the relation among various MMDs. Specifically, the modeling is done in a discrete manner to introduce the possible stochasticity that leads to varying results of team cognition. Furthermore, based on **Fig. 3-4** and **Fig. 3-5**, in order to build a “simulated environment” for a team to act, the performance indexes should be identified from the accident exploration

phase to present the overall system state. Then, the correspondence between performance indexes and deterministic scenarios should be determined to connect a team's evolving cognition, the system state, and corresponding scenarios. To define the parameters, the calculation of the system state is emphasized. One has to understand how performance indexes change during system performance and how the course of actions taken by a team affects the system state. The iterative calculation simulates how the scenario in an accident evolves.

2. **Execution:** To achieve FETC properly, data collection, verification, and validation are performed. In this thesis, for every possible scenario, the probability distribution of each operational disconnect is established to calculate how a collaborative decision is made. Furthermore, a verification procedure is compulsory to ensure model reliability [103]. In addition, a sensitivity test is conducted to identify the parameters dominating the simulation results. Ideally, a model's function should not be significantly affected by changes in any parameter. Lastly, the model's outputs should also be validated to ensure the simulation reflects real-world situations. The simulation results must be compared with system performance in reality. In general, empirical observation is the most common approach [102, 106].

3. **Result analysis:** For simulation, a sufficient number of runs are needed for data

convergence. The frequency of operational disconnects that occur is recorded to present the pattern of MMDs in an accident. Accordingly, we can achieve a more comprehensive examination to unravel possible breakdown during team coordination, facilitating error prevention in the future.

3.4.2. Possible challenges and corresponding strategies

FETC is a simulation-based approach with both quantitative and qualitative characteristics. Furthermore, the concept of role-specific SMMs has not been well discussed by mainstream research. Therefore, some potential challenges during the implementation are expected. In this section, these challenges and corresponding strategies for solutions are elaborated.

3.4.2.1 Challenges in identifying team cognition

Based on the technical framework, the CDM serves as a framework for exploring the context of an accident. In the original version of CDM, the analysis is based on participants' memory regarding the accident that occurred. However, the result of the cognitive interview is subjective [120, 121]. The participants may miss critical decision points, which can only provide fragmented understanding regarding the accident. To prevent this, the workflow of the team defined by task analysis can serve as an additional tool during the interview, functioning as a guideline for participants to

provide a clearer context.

An MMD is identified when a party is unable to provide acceptable solutions that meet team members' expectations. However, contradicting statements are also possible. For example, a team consists of two parties, that is, A and B. A states that B does not provide an acceptable solution, whereas B asserts that they have actively supported A's expectations. This contradiction reflects that B's practices are yet to be well regulated and acknowledged by A. Therefore, A's concerns are still treated as MMDs.

Lastly, the mapping of identified MMDs also requires careful consideration. To ensure the appropriateness of the mapping, one should understand how the system performs. Accordingly, the execution of task analysis described in the first paragraph is highly recommended for clarifying the workflow in advance. In addition, expert assessment is a suitable option, which is commonly used to examine the accuracy of SMM measurement [89].

3.4.2.2 Challenges in ABM development

For performing smooth ABM, the qualitative examination described in the previous section is a critical fundamental process. By mitigating the aforementioned possible challenges, the comprehensiveness and accuracy of the agent-based model can be ensured. However, in this work, some potential challenges in data collection and model validation should be considered. First, for the data collection, as mentioned, the

probability distribution of operational disconnects is the major data input. However, in the aviation industry, because of the extremely low probability of adverse events, observation of how well-trained operators make mistakes is difficult. Furthermore, the data collected in the reporting system may not include occurrences of interaction conflicts or underlying decision-making processes. Therefore, approaches such as a questionnaire or a lab experiment are alternatives that can be considered.

For model validation, in general, the model's outputs should also be validated to ensure the simulation reflects the real-world situations. Empirical observation is the most common approach for such validation [102, 106]. However, similar challenges are also expected in this process. It will be extremely difficult to observe the occurrence of an accident. To overcome this challenge, comparing the data structure of real-world and ABM outputs is a possible alternative [107].

3.5 Summary

In this thesis, the defined role-specific SMM leverages the effects of potential MMDs in an MTS. The compatibility between operators is emphasized, facilitating operators to work together in a heterogeneous system. Accordingly, the negative effects of MMDs in team cognition can be clearly elucidated. Then, FETC is accordingly proposed to study evolving team cognition in a longitudinal manner. Specifically, the content of Section 3.4.1.1 associated with the content of Chapter 4. Chapter 4 presents

a model to explore the context of team cognition from the perspective of MMDs.

Furthermore, Section 3.4.1.2 provides a basis for Chapter 5 in ABM development.

Along with the technical framework, some strategies are also elaborated to overcome potential challenges in order to achieve smooth elaboration.

4 . Accident exploration and MMD mapping

This chapter aims to explore the context of an unstable approach from the perspective of mental model disconnects (MMDs). The structure of team cognition during aircraft landing will be correspondingly constructed and presented to clarify how various MMDs between pilots and air traffic controllers (ATCOs) jointly contribute to defective team cognition. Nine pilots and seven ATCOs are recruited to conduct the crew-based critical decision method. The shared mental models (SMMs) of both parties are compared to identify the MMDs associated with their interaction conflicts during landings. A key discovery of this research is that the MMDs in task-related SMMs make integration of various working results difficult, which requires additional interaction to mitigate the contradiction in requirements. Furthermore, the conflicting disconnects caused by various subjective priorities in a heterogeneous system are also identified, which requires further negotiation between the parties to achieve a mutually beneficial outcome. In team-related SMMs, MMDs make it difficult for different parties in a system to coordinate respective requirements of members and they impede the prevention of system risks, resulting in continuation of risky operations. Finally, the coordination of these SMMs forms a robust loop in which

a system can actively detect and address the potential risks.

4.1 Introduction

As discussed in Chapter 1, for the landing system involving a heterogeneous team, team interaction is critical yet challenging to form holistic team cognition [36, 55]. The heterogeneity, unequal information sharing, and limited time are some causes for possible MMDs [12, 64-66]. The misaligned mind makes a team prone to conflicts, causing defective team cognition and system errors. To understand the involvement of MMDs during coordination, this chapter aims to answer two fundamental questions: (1) What MMDs occur during interaction and what is their corresponding causal relationship? (2) What interaction (implicit and explicit) conflicts are caused and what ultimate team cognition is formed?

First, as discussed in Section 2.2, MMDs can be categorized into informational, evaluative, and operational disconnects [41, 71]. In general, the identification of operational disconnects is critical to pinpoint immediate risks to be considered. It can also be a leverage point to examine relevant informational and evaluative disconnects. For example, the ATCO's instructions such as high-speed clearance or instruction to take a short-cut may sacrifice pilots' time for operating the aircraft, leading to possible conflicts [12, 43]. In such case, for ATCOs to manage the overall air traffic flow, cross-utilization of information is crucial to comprehend the overall picture of the airspace

and relevant items including separation, location, heading, or relative airspeed of aircraft [122, 123]. However, the details of an individual aircraft are not of major concern, which causes informational disconnects and corresponding evaluative disconnects. Therefore, with the active clarification of such a causal relationship between MMDs, a more comprehensive understanding regarding a system's potential loopholes can be investigated. In addition, it can be fundamental for breakdown elimination in the future.

As for the second question, proper MMD mapping can provide suitable answers. Based on Section 2.3, the interaction conflicts can be a product of aggregated MMDs. The combination of these interaction conflicts also characterizes the formed team cognition. Therefore, clarification of such connection is vital to demonstrate the involvement of MMDs in team interaction. To achieve this, the interaction mechanism of an MTS should be defined. As discussed, the pattern of interaction adopted is subjected to the structure of an MTS [46]. For a between-component team, a landing system in this case, both implicit and explicit interactions are required. The reciprocal interaction in a between-component team requires different parties to achieve designated sub-goals by performing the respective tasks. Thus, implicit interaction should be conducted first, which enables a party to perform the tasks such that the system's current needs are satisfied. However, if the results of implicit interaction are

unsatisfactory, conflicts occur. The improper instructions from ATCOs [12, 43] or the execution of efficient approach from pilots[48] are some examples of faulty implicit interaction. To mitigate the conflicts, explicit interaction should be initiated for purposeful coordination. However, possible emotion of team members due to poor team spirit can degrade the quality of coordination [23]. It may even result in the team missing the window for risk elimination. Ultimately, defective team cognition forms. A report documented that the late initiation of go-around is strongly related with an unstable approach [113].

In sum, this chapter aims to clarify underlying MMDs between pilot and ATCOs during landing. In addition, by accomplishing MMD mapping, the context of possible interaction conflicts and defective team cognition can be clarified. The results of this chapter also serve as a critical fundamental for modeling an autonomous agent during the implementation of FETC proposed in Chapter 3.

4.2 Methodology

This section presents how the Critical-decision method (CDM) is implemented to explore the context of an unstable approach. The task flow is pre-identified for a smoother CDM execution. Relevant details are elaborated in the following section.

4.2.1. Task flow identification

In order to collect sufficient information for the implementation of FETC, the tasks flow involved in the incident needed to be identified to locate each of the decision points. Furthermore, it will be easier for participants to recall a more comprehensive decision-making process. Based on relevant research and International civil aviation organization (ICAO) appendix [12], the tasks flow during landing phase are identified in **Fig. 4-1**. Meanwhile, the mental process capabilities are also required.

Fig. 4-1 Task flow during the landing phase

In **Fig. 4-1**., the labels with rectangle represent the tasks needed to be executed. The tasks required during the landing phase is a repetitive loop until the aircraft is transferred to the tower controller. Although the tasks required are repetitive, the decisions needed to be made are subjected to the evolving scenario. For pilots, they

should control the aircraft properly to fit the stable approach criteria, meanwhile, the operations are mainly determined by the instructions given by ATCOs. Once pilots do not accept the instructions, a non-routine interaction will be initiated to solve the requirements mismatches. Then, the instructions will be executed until both parties agree with the decision.

4.2.2. Critical decision method

The CDM is an interview-based methodology commonly used to examine challenging events and elicit knowledge [116-118]. In this research, the crew-based CDM is proposed and applied to examine how the mental model disconnects influence events in a contextual way. The SMMs of both pilots and ATCOs are examined and compared to identify the respective mental model disconnects that must be corrected.

The overall structure of the project is demonstrated in **Fig. 4-2**.

Fig. 4-2 Structure of the crew-based CDM

4.2.3. Design procedure

The crew-based CDM consists of three steps. First, both parties are recruited to participate in the semi-structured interview. Second, a content analysis is executed to discern the respective SMMs. Last, the extracted SMMs are compared to identify the mental model disconnects in various categories.

In general, the CDM-based interview consists of four main parts, namely incident identification, timeline construction, deepening probes, and “what if” queries. The four parts are described below. (1) *Incident Identification*. Participants are asked to recall the incident to achieve an overall understanding of the event. (2) *Timeline Construction*. When participants are sharing their own decision-making process they are also required to elaborate on how the decision is made. (3) *Deepening Probes*. This section is the most critical part of the CDM, and it assesses the details of the decision-making. Extra deepening probes were designed to study individual SA, task-related SMMs, and team-related SMMs. 4) *“What if” Queries*. This is not a compulsory part of the CDM,

With respect to procedure, the content analysis is conducted through open coding to identify the meaningful themes that explain the SMMs. Then, the respective SMMs are compared. A flow chart of the procedure is presented in **Fig. 4-3**. To identify the requirements of role-specific SMMs, individual preferences concerning how teammates act during an interaction serve as a reference through which to examine

whether their team members possess the required SMM. Furthermore, both parties' assumptions concerning team members' actions are also compared to identify the derived MMDs from divergent priorities and heterogeneous goals.

Fig. 4-3 Procedure of content analysis and comparison

4.2.4. Participants

Both ATCOs and pilots are recruited to join the CDM-based interview. Because the CDM is a qualitative approach, no fixed number of participants must be recruited. To achieve adequate data thickness and richness, at least six participants should be involved [39, 40]. With respect to recruitment prerequisites, participating pilots should be at least first officers with one year of flying experience to exclude errors from immature skill and judgment. Similarly, ATCOs are required to possess at least one year of experience during which they acquired basic skills and experience in air traffic

flow management.

4.2.5. Questionnaire development

The questions used during the semi-structured interview were developed in light of the structure of the CDM. Incident identification and timeline construction were firstly conducted to re-build the story. Deepening probes were implemented to investigate both SA and SMM. The probes of SA examined one's decision-making comprising with the cues perceived, mental model, prediction and the corresponding goals finalized in scenarios. The probes of SMM is shown in **Fig. 4-3**, which explain the examination of one's SMM (task-related and team-related) and how a participant assumed team members.

Relevant questions are given below.

- *Incident identification and timeline construction (In this case, a figure is provided as an extra apparatus, shown in **Fig. 4-4**):*

- 1) Please describe the unstable approach event or relevant near-miss events that you experienced. Please also identify each of the decisions you made across the timeline.

Fig. 4-4 Sheet for storyline identification

- *Deepening probes (applied to each of the decision points identified):*
 - 1) **SA:** Please elaborate: What information and cues did you perceive that determined your actions? How did you comprehend the pattern of the cues? How did the current situation influence your prediction? What were your goals at that time?
 - 2) **Task-related SMMs:** Based on the foregoing discussion, which concepts do you think are most critical for you to integrate into your SMM to support your teammates' task performance? Contrariwise, which concepts do you think are most critical for your teammates to integrate into their SMMs to support your task performance?
 - 3) **Team-related SMMs:** During the interaction in contingent scenarios, how did you actively locate and coordinate each other's needs? What information was critical to be conveyed? Which concepts do you think are critical for your

teammates to possess in their SMMs to facilitate interactions and performance?

What information must your teammates provide?

- **“What-if” Queries:**

- 1) For the concepts you have mentioned, please apply them to the various scenarios (based on the context of the conversation).

4.3 Results

In this study, both ATCOs and pilots were recruited to join the semi-structured interview. Ultimately, seven ATCOs and nine pilots in Singapore were recruited. The profiles of the participants are provided in **Table 4-1**. Three sub-categories are included: (1) pilots’ mental model disconnects, (2) ATCOs’ mental model disconnects, and (3) conflicting disconnects.

Table 4-1 Profile of participants

Pilots	1	2	3	4	5	6	7	8	9
Age	31	32	40	60	52	25	50	52	57
Position	FO	FO	FO	Capt.	Capt.	FO	Capt.	Capt.	Capt.
Flying hour	1900	2000	3000	22000	30000	1450	18000	9000	12000
ATCOs	1	2	3	4	5	6	7		
Age	45	25	25	27	35	35	42		
Position	AC.	TC.	TC.	TC.	TC.	AC.	AC.		
Working years	10	3	3	2	7	6	8		

* FO: First Officer/ Capt: Captain/ AC: Approach Controller/ TC: Tower Controller

For pilots, six mental model disconnects were identified, all of which are listed in **Table 4-2**. First, under the task-related SMM, because of the unequal information sharing, the informational disconnect causes pilots to only perceive the limited surroundings with the Terrain collision avoidance system (TCAS) system; however, experienced pilots can fully utilize the limited information. As for the evaluative disconnect, ATCOs opined that some pilots may prioritize personal considerations such as fuel preservation or passenger comfort over air traffic flow. With respect to operational disconnects, pilots may not strictly follow instructions received from ATCOs; specifically, pilots may prefer an approach with a more gradual rate of descent, which impacts the separation between aircraft. Furthermore, when ATCOs attempt to expedite the landing process during peak hours, some pilots may lack sufficient preparation to comply with nonroutine instructions and are therefore unable to comply within the designated time.

Captain 4 mentioned how he utilized TCAS:

As we are flying the aircraft and we are not the only aircraft in the whole terminal area, the ATCOs are also talking to other aircraft at the same time when we can listen to the same radio channel. We would then have a general idea of the aircraft around so that we can access the situation while comparing the situation to what I see in the TCAS. If there are any good instructions by the ATCO, I would be able to hear as well

Approach controller 6 mentioned the importance of following instructions strictly:

So if the first aircraft descends slowly, the rest will descend very slowly. That's why once they reach the holding stack, they are very high.

Table 4-2. Pilots' mental model disconnects from ATCOs' perspectives

Category	Item	Comparison
<i>Task-related mental model disconnects</i>		
Informational disconnects	Limited information regarding the current air traffic flow	<p>Pilots' SMM: The only information resource for the current air traffic flow is the TCAS system, which only displays the location of nearby aircraft. Only an experienced captain is able to apply the limited cues to comprehend the surroundings (16).</p> <p>ATCOs' perspective: Before executing any operations, pilots should consider the overall air traffic flow (32).</p>
Evaluative disconnects	Prioritize other considerations over the air traffic flow.	<p>Pilots' SMM: Pilots' operations must account for fuel, gas emissions, and passenger comfort (13).</p> <p>ATCOs' perspective: Some pilots prioritize personal considerations such as fuel and comfort, which affects the execution of the instructions given (10).</p>
Operational disconnects	The instructions given may not be strictly followed.	<p>Pilots' SMM: In consideration of fuel consumption, gas emissions, and passenger comfort, pilots prefer not to decelerate or descend too early or quickly (13).</p> <p>ATCOs' perspective: Pilots should follow the instructions given. Otherwise, they may affect the separation among aircraft (15).</p>
	Insufficient preparations for nonroutine instructions during peak hours	<p>Pilots' SMM: Some pilots are unable to make sufficient preparations for the coming instructions (6). However, experienced captains can predict the coming instructions on the basis of the data collected from TCAS (27).</p> <p>ATCOs' perspective: During peak hours, ATCOs provide nonroutine instructions to rearrange the air traffic flow. It is better for pilots to be familiar with these and prepare for possible nonroutine instructions (5).</p>
	ATCO instructions may not be	<p>Pilots' SMM: Experienced pilots are able to prepare for the coming instructions in advance on the basis of the aircraft's current state and promptly</p>

	timely achieved.	accomplish the instructions (10). ATCOs' perspective: Pilots should make appropriate preparations to respond to and accomplish the instructions given (12).
<i>Team-related mental model disconnects</i>		
Operational disconnects	Requesting last minute changes	Pilots' SMM: Pilots attempt to offset excessive energy to stabilize the aircraft at the first opportunity (8). If the aircraft cannot be stabilized, further communication is initiated to seek extra instructions as necessary (8). ATCOs' perspective: When pilots cannot comply with the instructions, they should communicate their difficulties as early as possible rather than requesting last minute changes (11).

*The number in brackets represents the frequency of mentions by participants.

On the other hand, one operational disconnect was identified concerning the team-related SMM. When pilots are in an unstable landing state, they tend to overly focus on correcting the excessive airspeed or altitude rather than immediately initiating extra interaction with the ATCOs. Consequently, if pilots are unable to manage the excessive energy in a timely fashion, a late communication requesting extra distance forces ATCOs to rearrange the current air traffic flow.

Tower controller 6 mentioned the importance of requesting timely assistance:

Providing ATCO with information like if they cannot adhere to the speed. They have to inform ATCOs earlier so the ATCOs can plan for them.

For ATCOs' mental model disconnects, five items were identified, which are detailed in **Table 4-3**. First, for task-related mental model disconnects, the informational disconnects concern the unequal information sharing that causes ATCOs to be ignorant of the exact weight of the approaching aircraft. Thus, ATCOs struggle to determine the proper instructions to issue to suit various requirements. As for operational disconnects, providing instructions without considering an aircraft's particular capabilities may increase the burden of compliance for pilots, especially in the expedited landing process during peak hours. Consequently, an aircraft is more likely to enter a state of excessive airspeed or altitude.

Participants 7 (Captain) thought ATCOs should know the capabilities limitation:

The ATCO needs to know the aircraft's performance as well. It is not that simple. The speed up and slowdown are at different rates. There is an issue of wake turbulence as well, therefore, you cannot put the aircraft too close. You have to fit the combination properly as well

Some team-related mental model disconnects were also identified. First, ATCOs may sometimes fail to provide instructions in a timely fashion. Late intervention reduces the time available for pilots to comply with the request or modify the instability. For the other two operational disconnects, pilots opined that it is better for ATCOs to actively provide contextual information or details of the instructions because doing so enables pilots to make plans in advance.

Participant 9 (Captain) mentioned the importance of information provision:

During the communication, as long as ATCOs provide the remaining track miles and assigned airspeed, then I will be able to enact a plan accordingly.

Table 4-3. ATCOs' MMDs from pilots' perspectives

Category	Item	Comparison
<i>Task-related mental model disconnects</i>		
Informational disconnects	Insufficient information regarding each of the aircrafts	<p>ATCOs' SMM: In the current system, ATCOs have limited knowledge of the exact payload of aircraft (5), which makes it difficult for ATCOs to determine suitable instructions for all the various types of aircraft (5).</p> <p>Pilots' perspective: ATCOs should know the various capabilities of aircraft to provide better instructions (13).</p>
Operational disconnects	The instructions may cause pilots to be unable to stabilize.	<p>ATCOs' SMM: During peak hours, ATCOs will request high-speed clearance or shortcuts to expedite landings (10). However, if an aircraft becomes unstable, extra instructions are given to ensure the aircraft can return to the correct landing profile (17).</p> <p>Pilots' perspective: ATCOs should consider whether the instructions they give appropriately enable pilots to remain in a stabilized landing state (11).</p>
<i>Team-related mental model disconnects</i>		
Operational disconnects	The late provision of instructions causes pilots difficulty in performing operations appropriately.	<p>ATCOs' SMM: ATCOs will actively inform pilots of their current airspeed (6). Where necessary, ATCOs will intervene to address excessive airspeed (15) or altitude (13).</p> <p>Pilots' perspective: Further instructions may come too late, which reduces the time available for pilots to perform requested operations. This scenario is particularly common for heavier aircraft (15).</p>
	Insufficient provision of contextual	<p>ATCOs' SMM: Where possible, ATCOs will actively provide contextual information such as weather (2), current traffic (3), or the runway</p>

information for pilots	situation (3) to help pilots make more accurate predictions (11).
	Pilots' perspective: Information regarding the surrounding air traffic flow helps them to make preparations (5).
Insufficient provision of details of the instructions given	ATCOs' SMM: None
	Pilots' perspective: The provision of track miles and required speed from ATCOs is necessary for them to plan coming actions (9).

*The number in brackets represents the frequency of mentions by participants.

Conflicting disconnects arise because of the divergent priorities of pilots and ATCOs. Two disconnects were identified and are presented in **Table 4-4**. First, pilots and ATCOs had divergent views with respect to fuel conservation. Pilots opined that ATCOs should consider remaining fuel when providing instructions. ATCOs contended that pilots should prioritize the overall air traffic flow. With respect to weather avoidance, pilots expressed a preference for avoiding weather patches where possible; typically, ATCOs are able to comply with this preference. However, if the aircraft is nearing the final approach fix, ATCOs will vector the aircraft to pass through weather patches to maintain the current air traffic flow.

Captain 7 mentioned the contradicted considerations of weather avoidance :

If there is a storm ... Sometimes we might ask for shortcuts for avoiding weather. We would have to ask for it ourselves. I would not want to wait till the ATCOs give the instruction. The radar might not pick it up as clearly by the ATCOs. The ATCO might not be able to see it the way the pilot do. There are different thresholds of different pilots to avoid the weather. Usually, every pilot will ask it is only a matter of how much deviation the pilot wants... The ATCO can tell that aircraft coming

from that direction would have a problem with their route.

Table 4-4. Conflicting disconnects

Category	Item	Comparison
Evaluative disconnects	Fuel preservation	Pilots' SMM: ATCOs should realize pilots' are concerned with fuel preservation during a landing (9).
		ATCOs' SMM: Pilots should prioritize the maintenance of the air traffic flow over secondary considerations such as fuel or passenger comfort (10).
	Weather avoidance	Pilots' SMM: Instructions should be tailored to the airspace conditions, especially for the weather conditions (8).
		ATCOs' SMM: Pilots should adhere to ATCOs' instructions regarding weather avoidance to ensure smooth traffic flow (7).

*The number in brackets represents the frequency of mentions by participants.

4.4 Discussion

For pilots, in terms of the task-related SMM, three operational disconnects were identified. First, ATCOs mentioned the improper execution by pilots of the instructions given, which was determined to be caused by evaluative disconnects. Due to the prioritization of fuel consumption and passenger comfort, pilots can not strictly follow the instructions. For the other two operational disconnects, it was reported that pilots cannot be able to accomplish the instructions timely because of insufficient preparations, and this is caused by limited information regarding current air traffic flow. Ultimately, two undesirable consequences can occur. One is an improper landing state with

excessive altitude or airspeed, and the other is the impact on ATCOs' separation management. Especially in the scenarios of excessive altitude or airspeed, the major team-related mental model disconnect is likely to occur. Pilots will attempt to mitigate the poor landing profile as quickly as possible [11, 48], which causes them to miss the window for requesting extra track miles from ATCOs. The late initiation of communication causes ATCOs difficulty with timely interventions, a result that can be attributed to over-confidence and continuation bias [19].

For ATCOs, in terms of the task-related mental model disconnects, unequal information sharing impairs their ability to know the exact payload of an aircraft, which contributes to the corresponding operational disconnects at peak hours. To manage numerous aircraft, nonroutine instructions such as high-speed clearance or taking a shortcut are provided. However, insufficient information they possess makes it difficult for ATCOs to account for the various requirements of aircraft when issuing the instructions. Relevant research has also indicated that some instructions can push an aircraft past its limitations [12, 43]. On the other hand, for the team-related mental model disconnects, it was reported that the untimely provision of further instructions decreases the time available for pilots to execute the instructions or detect the risks. This scenario is especially difficult for pilots of heavy aircraft because they require significantly more time to execute the instructions. Furthermore, to improve the quality

of interactions, pilots expressed the hope that ATCOs would provide more information regarding surroundings and landing pattern intentions to give pilots more accurate prediction ability of landing factors.

With respect to conflicting disconnects, they exhibit different characteristics from the aforementioned mental model disconnects. Owing to the contradictory subjective priorities attributable to heterogeneous goals, it is likely for a party to compromise on another party's resource to optimize their own performance. Consequently, this inevitably leads to conflicts during the interaction. In the case of a landing, the study identified key issues of weather avoidance and fuel preservation. In sum, rather than preventing the conflicting disconnects from occurring, the key is to balance the respective requirements in the design of the system.

Fig. 4-5 depicts an overall flow chart of various disconnects. The key takeaway is that the absence of centralized management in a distributed system requires all the parties that possess congruent SMMs to coordinate their respective roles and fit the system's requirements. The mental model disconnects identified herein impair interactions between parties in various ways. First, the mental model disconnects with respect to task-related SMMs cause performance results that defy team members' expectations and are incompatible with system goals. The unsatisfactory integration of the respective working results makes an aircraft under such scenarios prone to unstable

approach. For pilots, the insufficient surroundings information and the prioritization of secondary considerations are the major factors which cause the defective execution of ATCO's instructions. Similarly, the limited information regarding the approaching aircraft makes ATCOs challenging to provide suitable instructions. Except for the mental model disconnects mentioned above, the conflicting disconnects resulting from competing priorities can make it more difficult for the team to satisfy their respective requirements in a mutually satisfactory manner. One party can even compromise on another party's resource for their own priorities. The contradicted preference regarding weather avoidance is one typical example. Consequently, further negotiation which requires descent team-related SMMs is necessary. Either pilots or ATCOs needs to initiate interactions timely to adjust the landing profile. Otherwise, the unsolved conflicts evolve into adverse events. In this case, both pilots' last-minute requests and ATCOs' late provision of instructions are the major breakdowns needed to be mitigated.

Beyond the effects of mental model disconnects, this study examined how appropriate SMMs facilitate system performance. Specifically, operators having the appropriate task-related SMM can actively satisfy their team members' expectations, and only simple interactions are necessary to confirm the execution of system operations. Relevant research documented silent coordination can occur where team members possess aligned SMMs, through proper monitoring of the system's state,

operators are capable of adapting themselves to the current needs [45]. For example, experienced captains can actively use the TCAS system or listen to radio channels to predict and prepare for the coming instructions given by ATCOs. Senior ATCOs can predict pilots' intention based on their route, or aircraft's type. As a result, the proactive measures executed help to minimize the interactions required. Based on the results obtained, the unequal information sharing is the major factor which causes task-related operational disconnects. While, experienced operators are capable of collecting and utilizing limited information to overcome the informational disconnects, decreasing the occurrence of operational disconnects. Therefore, the improvements in information sharing in the landing system deserve more attention. As a matter of fact, numerous research has appreciated the importance of information transparency in a system [45, 124, 125]. However, relatively unnecessary information is "noise information", which not only increase mental workload but also impede operators from finding critical information [14, 70]. Therefore, it is crucial to pinpoint the key information needed to be added in future research. Specifically, how the respective SMMs are benefited from the mutual information added should be articulated. furthermore, explicit interactions between parties serve as a safety net to prevent the execution of unwanted operations. The early initiation of interactions enables the team to address potential risks as soon as possible. This interaction between task- and team-related SMMs characterizes a

reliable system.

Fig. 4-5 MMDs in the landing system

4.5 Summary

In this research, unstable approaches were examined from the perspective of team interactions and MMDs. This study's findings make both theoretical and practical contributions, which are summarized as follows.

Theoretical contributions. It was determined that two categories of SMMs (task and team-related) operate contextually and are critical in a complex system. Because of the lack of centralized management in an MTS, appropriate SMMs are crucial for operators and the system as a whole to achieve mutually beneficial coordinated goals. Mutual coordination between these two SMMs gives rise to a feedback loop through which a system can actively detect and address the potential risks. Specifically, the task-related SMM facilitates the implicit integration of respective working results, and the team-related SMM helps to achieve coordination of nonroutine interactions to prevent errors. However, the underlying conflicting disconnects pose a threat to the quality of team interaction. The inconsistent evaluative criteria cause a party to compromise on another's a resource for their own needs.

Practical contributions. Correcting the mental model disconnects identified herein can lead to effective improvements regarding landing safety. First, implementing data link in the future could enable all stakeholders to attain a coordinated understanding of the current operational status, and could decrease the potential informational

disconnects and corresponding operational disconnects. More research should be done to elicit the critical information needed to be displayed in the future data link system. Furthermore, some operational disconnects can be effectively avoided through experience. These findings could be used to develop critical training materials for beginners to learn to actively satisfy the system's requirements rather than over-focusing on one's own respective tasks.

In all, the result of this part provides a comprehensive understanding of the involvement of MMDs during the coordination process. The importance of implicit interaction and SMMs are also clearly stated and presented for future research. Furthermore, the MMD mapping developed play as critical fundamental for the ABM development in the coming section.

5 . Implementation of FETC in an unstable approach

This chapter aims to implement the framework of evolving team cognition (FETC) to study a team's evolving cognition from the perspective of mental model disconnects (MMDs). To achieve this, agent-based modeling (ABM) is adopted to simulate the involvement of MMDs in both implicit and explicit interactions in an iterative manner. Based on the results of the simulation, the occurrence of MMDs greatly increases in case of aircraft approaching the terminal area. For the scenario of landing in an outer area between 100 and 50 Nautical miles (Nm), the task-related MMDs are more frequent, causing incompatible working result of parties. It reveals the necessity of additional coordination in order to avoid system risks stem from the conflicts between parties. As for the landing around the terminal area (30–15 Nm), team-related MMDs prevail, giving rise to passive information dissemination regarding changing conditions and late initiation of urgent coordination. These MMDs in task-related SMM cause a team to miss the window for preventing an adverse event from occurring.

5.1 Introduction

In this chapter, FETC is implemented to model team cognition in an unstable

approach. For this purpose, ABM is a flexible approach to study the qualitative characteristics of MMDs. As stated in Section 3.3, the team comprising pilots and ATCOs is treated as an autonomous agent, while evolving team cognition determines the rule a team applies in response to a certain scenario. To bridge the requirement for ABM in the later section, this chapter aims to answer the fundamental question: How to model the dynamic aeronautical environment properly?

First, for the simulation modeling of an accident, the “rare event problem” should be considered [126]. In a complex system, extremely low-probability accidents render simulation time consuming and ineffective. While the characteristics of FETC can partially mitigate this issue, operational disconnects identified in MMD mapping can be the hotspot during coordination, narrowing down the items to be focused. The modeling of a dynamic and continuous aeronautical environment also should be considered to avoid the rare event problem. As discussed in Section 3.4, the system state should be defined to determine the corresponding scenario. A decent trade-off must be achieved between the continuity and discreteness of the variables [127]. The key is to identify the threshold at which the operator can differentiate one scenario from another. Take airspeed in the case of an unstable approach as an example. If an aircraft’s airspeed is higher than the requirement in stable approach criteria when it reaches the stabilization height, it is deemed a scenario prone to an unstable approach. However, if

an aircraft is at the outer area with sufficient time, the airspeed should be at least 20 knots higher than standard terminal arrival routes (STARs). Therefore, operators can treat it as a scenario prone to landing instability. Such requirements also reflect the importance of conducting comprehensive context exploration in the CDM-based interview.

To sum, as discussed in Section 3.3, through the rotation between implicit and explicit interactions, a team's SMMs can be integrated to form team cognition required to adapt to changing conditions. Such an interaction process can be modeled as algorithms for a team to dynamically determine suitable course of actions. Nevertheless, the underlying MMDs can act as loopholes, which cause varying actions, thereby generating system risks. The emerged system risks must be detected and addressed in a timely manner; otherwise, the accumulation of risks may evolve into adverse events. Therefore, the identification and elimination of these loopholes, that is, MMDs, is crucial for achieving effective accident prevention.

5.2 Methodology

In this research, FETC is proposed and implemented into the development of an ABM. This section consists of four phases: (1) FETC development, (2) ABM development, (3) Data collection, and (4) Model validation.

5.2.1. Environmental setting

STARs are regulated for aircraft to follow. In general, the altitude or airspeed required are based on the airport design, surrounding terrains, or noise abatement regulations. In this research, the investigation conducted is based on Changi airport, Singapore. Thus, the STARs implemented in Changi airport are simplified and used to develop the environment of simulation. Specifically, five STARs with ranges from 100 to 10 Nm are considered (see **Fig. 5-1**). As the aircraft passing a STAR, the interaction between pilots and ATCOs is initiated to determine the way aircraft maneuvers. In order to simplify the simulation, the near-miss scenarios of unstable approach are emphasized. To achieve this, the requirements of the last STAR, STAR 5, is set to be 3000 ft /170kt. The landing without satisfying the requirement of STAR 5 is recorded. Based on the definition, a landing can be deemed as an unstable approach when an aircraft cannot satisfy the stable approach criteria (required airspeed and altitude) by decision height (DH): 1000 ft. In real-life scenario, before reaching the DH, such near-miss scenarios can be corrected by executing aborted approach. However, the execution of aborted approach is subject to several factors, including the coordination between approach controllers and tower controllers, runway management, air traffic flow management around terminal area, etc. Therefore, the execution of aborted approach is removed in this simulation.

Fig. 5-1 Aircraft as different agents at different STARs

5.2.2. Agent logic

As stated in Section 3.3, the team consists of different parties is set to be an agent which acts according to the team cognition. In general, pilots' operations are subject to the instructions given by ATCOs. The results of interaction between parties ultimately determine how an aircraft maneuver. Therefore, in this research, aircraft were treated as agents whose actions reflect the results of team cognition formed. In order to establish the algorithms for agent logic, both implicit and explicit interaction for the between component team. In this work, a general logic for routine interaction is established to simulate a regular landing process. Then, the underlying MMDs should be articulate to model team interactions. Based on the previous work done [16, 38], possible operational disconnects are presented in **Table 5-1**. As discussed in Section 2.2, among all the categories of MMDs, operational disconnects can cause direct and observable risks during team interaction. Thus, operational disconnects are mainly

considered for model simplification and feasible data collection.

Table 5-1 Interaction according to SMM inconsistency

Mental model disconnects in implicit interaction (task-related SMM)		
<i>Operators</i>	<i>Items</i>	<i>Description</i>
Pilots	<i>Operation 1:</i> The instructions given may not be strictly followed or completed timely.	Due to fuels preservation, gas emissions and passenger comfort, pilots prefer not to descend or decelerate too early, leading to late accomplishment of the instructions.
	<i>Operation 2:</i> Unresponsive to the instructions with potential risks.	Pilots should have the critical thinking to estimate the appropriateness of the instructions given and reflect their concerns to ATCOs where needed.
ATCOs	<i>Operation 3:</i> Provide non-routine instructions for arranging air traffic flow.	To fully utilize the current air space, nonroutine instructions like high-speed clearance, taking a short cut or late descent are given. It increases the uncertainty for pilots to stabilize the aircraft.
	<i>Operation 4:</i> Insufficient considerations of aircraft's requirements difference.	The unequal information dissemination makes ATCOs unable to know the exact payload of aircraft, which jeopardizes the provision of suitable instructions.
Mental model disconnects in explicit interaction (team-related SMM)		
Pilots	<i>Operation 5:</i> Persistence in addressing the improper energy state	When the landing stability is questionable, pilots insist on managing the energy state immediately rather than asking for extra instructions from ATCOs.
	<i>Operation 6:</i> Requesting last minute changes	Pilots initiate last minute changes for stabilizing the aircraft, which makes ATCOs hard to provide immediate support.

ATCOs	<i>Operation 7:</i> Late intervention with the corrective instructions.	The corrective instructions are not given timely, which decreases the time available for pilots to maneuver the aircraft.
	<i>Operation 8:</i> Insufficient reminders for pilots to notice their current landing state.	When the aircraft's stability is subject to factors like weather, separation, or their own landing state, not all the ATCOs remind pilots for taking care of the landing state.
	<i>Operation 9:</i> Insufficient provision of surrounding information for pilots.	Under the scenarios prone to unexpected changes, pilots expect extra information regarding current air traffic flow or weather patches for a better situational understanding.
	<i>Operation 10:</i> Insufficient provision of details of the instructions given.	When ATCOs are providing nonroutine instructions due to urgent needs, ATCOs do not provide sufficient intention expression or details for pilots to understand their purposes.

Fig. 5-2 illustrates the relationship among the operational disconnects and how the system errors emerge. The agent logic mechanism is based on the FETC as shown in **Fig. 3-4**. Actions are determined by the team cognition formed during the interaction. As an action is being carried out, the system state updated triggers new scenarios which require new rotation of interactions. In the case of the landing system, the reciprocal system with lateral integration between pilots and ATCOs requires a mix of both implicit and explicit interaction [46]. Logic functions of or ($\vee$) or and ($\wedge$) represent junctions determined by connection among operational disconnects. Junctions 1, 2, 3 and 4 refer to the system errors caused by mental model disconnects, whereas junctions 5 and 6 denote successful interaction preventing error occurrence:

- ***Junction 1:*** Mental model disconnects in task-related SMM impedes implicit interaction, causing incompatible working results between parties. Hence, further negotiation is necessary.

- ***Junction 2:*** Under scenarios with emerging demands, ATCOs cannot maintain sufficient information dissemination to provide pilots with a comprehensive situation understanding.

- ***Junction 3:*** Due to overconfidence, late initiation of interaction from pilots requiring additional help potentially occurs.

- ***Junction 4:*** Continuation of risky operations occurs when both parties fail to detect oncoming risks and actively initiate appropriate intervention in a timely manner.

- ***Junction 5:*** The team detects risky operations and prevents its execution. In general, when operators initiate an interaction for risk mitigation, team members always accede to their request.

- ***Junction 6:*** Both parties can perform their tasks to fulfill system requirements.

Fig. 5-2 Evolving team cognition in a landing system

5.2.3. Technical framework of ABM

The overall flow of the proposed ABM is depicted in **Fig. 5-3**. As an aircraft passes a STAR, the agent logic established will assess the current scenario and calculate the actions to be conducted. In this work, two variables are considered to simulate the scenario difference: 1) the progress of the landing (four sub-categories) and 2) the landing stability (two sub-categories). For the progress of landing (four STARs before reaching the decision height), as the time and distance reducing, a team's decision-making should change accordingly. Similarly, if an aircraft is prone to unstable approach (the aircraft is stable or unstable), a team should also perform the reactions required. Thus, in total, eight scenarios are determined. Correspondingly, eight sets of data should be collected and implemented in the logic (**Fig. 5-2**) to simulate how a team adapt to the changing conditions.

Based on the results of calculation, two types of actions, good and bad actions, are conducted. The parameters displayed in each of the actions represent the amount of airspeed and altitude which should be adjusted before reaching the next STAR. For the “good action”, the aircraft tries to achieve the required landing profile. By contrast, as for the “bad actions”, the aircraft does not strictly follow the STAR requirements and thus may fly at a higher airspeed, higher altitude, or both. Additionally, the consequences of bad actions will accumulate, leading to the deviated landing profile

which cannot be immediately mitigated. In this case, a team should conduct “good actions” to back to required landing profile as much as possible before reaching the next STAR [42]. Nevertheless, sometimes, the deviation may be too much to be addressed timely, which causes excessive airspeed or altitude in the end. Ultimately, if the aircraft cannot satisfy the requirements of STAR 5, the landing is deemed as a near-miss event of unstable approach. The frequency of the occurring operational disconnects is recorded for further analysis.

Fig. 5-3 An overflow of ABM

5.2.4. Data collection

The quality of the data collected as system input is fundamental to achieve realistic and predictive simulation. However, the characteristics of an unstable approach make

a proper data collection rather challenging. Generally, field observation or the database from the report system is the approaches commonly used. While, for the field observation, it is difficult to observe a highly-trained operator to make mistakes. As for the voluntary report system, it is also limited to record cognitive errors. Therefore, a survey is developed to cope with the issues above. Relevant details are presented in **Appendix 2**. The conditional probability of the mental model disconnects is collected, which helps to simulate the stochasticity of the interaction results.

5.2.5. Model verification & validation

For simulation-based research, a verification procedure is compulsory to ensure model reliability [103, 104]. Before explaining the meaning of the simulation outcomes, a sensitivity test should be conducted to identify the effects of different parameters on global outcomes. Ideally, a model's function should not be significantly affected by changes in any parameter. Even dominant parameters should affect the model reasonably and predictably. Based on the discussion in Section 2.7, three types of sensitivity analysis are presented, including the test based on OFAT, model-free output variance decomposition and model-based output variance decomposition. For the case herein, the sensitivity test based on OFAT was adopted due to the linear structure of the ABM (See **Fig. 5-2**). All the operations included in the model were set to be independent events. Therefore, there was no interaction among parameters.

Accordingly, each of the parameters can be tested respectively.

For the OFAT testing, the probability of all operational disconnects was set at 50% as a reference, whereas the tested parameter was set at 100%. Next, an independent t test was performed to examine statistical difference under the 95% confidence interval, with significance indicated by a p -value of <0.05 . The results are listed in **Table 5-2**, wherein no parameter is predominant.

Table 5-2. Sensitivity test

Items	T value / df	P value	Items	T value / df	P value
Operation 1	1.276 / 178	0.102	Operation 6	0.186 / 178	0.426
Operation 2	0.715 / 178	0.238	Operation 7	0.278 / 178	0.391
Operation 3	0.186 / 178	0.426	Operation 8	-0.388 / 178	0.349
Operation 4	-0.192 / 178	0.424	Operation 9	-0.591 / 178	0.278
Operation 5	1.199 / 178	0.116	Operation 10	0.1863 / 178	0.426

For simulation-based research, the model's outputs should also be validated to ensure the simulation can reflect the real-world situations. Empirical observation is the most common approach for such validation [102, 106]. However, the difficulties in data collection mentioned above make the validation process even challenging. Therefore, exploratory factor analysis (EFA) was performed as an alternative to examine the simulation's predictability. A survey for pilots and ATCOs was therefore developed to rate how strongly each operational disconnect related to unstable approach. Comparing

the simulation and survey results aids in determining whether the model reflects the experience of experts. Factor analysis is widely used in sociology to extract compound factors from large numbers of variables and explain variance in a data set. In this study, due to the relatively low number of the items (the operational disconnects included), the ratio of subjects-to-variables was set at 5 [128]: at least 50 participants were recruited for the 10 items.

5.3 Results

To collect the data for ABM simulation and the coming validation, 31 ATCOs and 21 pilots are recruited to finish the survey. Participants' profile is shown in **Table 5-3**. Meanwhile, **Table 5-4** shows the probability of the operational disconnects involved. Each of the operational disconnects has eight sets of data to simulate how the team reacts to the evolving scenarios. In total, 400 simulation runs are performed to reach a proper data convergence, together with 142 instances of unstable approach recorded. For a simulation research, achieving data convergence is a critical step for collecting validated data. As shown in **Fig. 5-4**, the data reached a stable convergence when around 120 events of unstable approach were collected. To facilitate understanding, three different perspectives are considered to explain the simulation results: 1) overall landing procedure, 2) landing between 100 and 50 Nm (airspace at the outer area), and (3) landing between 30 and 15 Nm (airspace around the terminal area). Furthermore,

the landing profile during an unstable approach is also recorded to present the maneuver of an aircraft. Ultimately, EFA is conducted to analyze both of the simulation and survey results as a validation procedure. Relevant details of raw data is displayed in

Appendix 3

Fig. 5-4 The trend of data convergence

Table 5-3. Participant profile of ABM developing

<i>Pilots</i>	<i>Number</i>	<i>Age (sd)</i>	<i>Flying hour (sd)</i>
Total	21	33.67 (8.94)	3638 (4780)
Second officer	2	28.5 (1.5)	196 (103)
First officer	12	28.92 (2.33)	2050 (790)
Captain	7	43.29 (9.53)	7342 (6785)
<i>ATCOs</i>	<i>Number</i>	<i>Age (sd)</i>	<i>Working year (sd)</i>
Total	31	28.97 (2.22)	4.21 (2.15)
Tower Controller	20	29 (2.55)	4.48 (1.78)
Approach Controller	11	28.91 (1.44)	3.8 (2.75)

Table 5-4. Parameters and values in different scenarios.

<i>The operational disconnects</i>	<i>Landing state</i>	<i>The landing profile</i>			
		STAR 1	STAR 2	STAR 3	STAR 4
1. The instructions given may not be strictly followed or completed timely.	Stable	12.74%	16.45%	21.94%	28.71%
	Unstable	14.84%	18.23%	23.71%	34.84%
2. Unresponsive to the instructions with potential risks.	Stable	9.84%	12.74%	17.26%	27.58%
	Unstable	12.10%	15.48%	21.77%	34.19%
3. Provide non-routine instructions for arranging air traffic flow.	Stable	17.86%	20.48%	22.62%	21.90%
	Unstable	15.24%	19.29%	26.67%	30.95%
4. Insufficient considerations of aircraft's requirements difference.	Stable	16.19%	18.57%	27.14%	35%
	Unstable	15.48%	18.33%	30.48%	41.19%
5. Persistence on addressing the improper energy state	Stable	12.26%	14.84%	22.26%	29.35%
	Unstable	15.16%	20.32%	25.81%	33.23%
6. Requesting last minute changes	Stable	10.81%	15.97%	20.48%	27.90%
	Unstable	12.74%	17.10%	21.29%	35.97%
7. Late intervention with the corrective instructions.	Stable	10%	10.24%	15.48%	27.14%
	Unstable	9.52%	10.24%	20.71%	37.38%
8. Insufficient reminders for pilots to notice their current landing state.	Stable	14%	16.25%	20.5%	37.25%
	Unstable	12.25%	15.25%	22.75%	50.25%
9. Insufficient provision of surrounding information for pilots.	Stable	19.29%	20.48%	28.33%	30.50%
	Unstable	16.19%	20%	30%	35.50%
10. Insufficient provision of details of the instructions given.	Stable	18.24%	19.76%	29.43%	29.43%
	Unstable	16.21%	21%	32%	35.73%

5.3.1. Operational disconnect pattern

This section presents the frequency of operational disconnects in an unstable approach scenario. The overall pattern is shown in **Table 5-5**, and the number of operations can be referred to **Table 5-1**. Apparently, the evolving landing progress causes significant pattern difference among three of the scenarios, with their frequency evidently increasing radically as the aircraft approached the terminal area.

Table 5-5. Pattern of operational disconnect occurrence.

Table 5-6. Paired *t* test between operational disconnects

		Landing between 30 and 15 Nm									
		Op_1	Op_2	Op_3	Op_4	Op_5	Op_6	Op_7	Op_8	Op_9	Op_10
Landing between 100 and 50 Nm	Op_1			0.328 / 0.744	- 0.551 / 0.583	- 4.279 / 0*	- 4.808 / 0*	- 9.584 / 0*	- 4.718 / 0*	- 5.489 / 0*	- -5.048 / 0*
	Op_2	0.563 / 0*		- 0.678 / 0*	- 10.04 / 0*	- 14.54 / 0*	- 12.68 / 0*	- 20.75 / 0*	- 14.17 / 0*	- 14.24 / 0*	- 14.506 / 0*
	Op_3	- 1.508 / 0.134	-7.07 / 0*		- 0.920 / 0.359	- 4.871 / 0*	- 4.664 / 0*	- 9.433 / 0*	- 5.646 / 0*	- 6.114 / 0*	- -5.831 / 0*
	Op_4	- 1.013 / 0.313	- 7.079 / 0*	0.452 / 0.652		- 3.481 / 0.001 *	- 3.175 / 0.002 *	- 7.061 / 0*	- 3.909 / 0*	- 4.212 / 0*	- -4.153 / 0*
	Op_5	0.323 / 0.747	- 5.115 / 0*	2.171 / 0.032 *	1.224 / 0.223		0.108 / 0.914	- 4.093 / 0*	- 0.377 / 0.707	- 1.173 / 0.243	- -0.881 / 0.380
	Op_6	0.323 / 0.747	- 5.875 / 0*	2.171 / 0.032 *	1.309 / 0.193	0 / 1		- 4.125 / 0*	- 0.477 / 0.634	- 1.119 / 0.265	- -0.905 / 0.367
	Op_7	2.148 / 0.033 *	- 4.098 / 0*		2.503 / 0.013 *	1.632 / 0.105	1.632 / 0.105			2.840 / 0.005 *	

	Op_8	-	-			-	-	-		-	
		0.294	-		0.927	0.588	0.631	2.001		0.749	
		/	6.584	1.73 /	/	- /	/	/		/	-0.543
		0.769	/ 0*	0.086	0.356	0.557	0.529	*		0.455	/ 0.588
	Op_9	-		-	-	-					
		3.313				3.201				-2.72	
		/	-	1.237	1.297	/	-	-		/	
		0.001	7.898	/	/	0.002	3.657	0.511		0.007	0.238 /
		*	/ 0*	0.218	0.197	*	/ 0*	5 / 0*		*	0.812
	Op_10	-		-	-	-	-			-	
		2.297				3.001	2.777			2.137	
		/	-	0.537	0.733	/	/	-		/	0.728
		0.023	7.438	/	/	0.003	0.006	4.358		0.034	/
		*	/ 0*	0.592	0.465	*	*	/ 0*		*	0.468

To present a clearer explanation among the operational disconnects, paired t test is conducted, which is shown in Table 5-6. The upper triangle denotes the results of the scenarios between 30 and 15 Nm, and the lower one denotes to the scenarios between 100 and 50 Nm. For the landing at the outer area (100 to 50 Nm), there is no significant difference between task and team-related operational-disconnects. Specifically, operations 3, 4, 9 and 10 are the disconnects with relatively higher frequency. On the other hand, the scenarios around the terminal area (30 to 15 Nm) exhibited a significant pattern difference between task- and team-related operational-disconnects. The frequency of all team-related SMM operations was significantly higher than that of all task-related SMM items. Among all the team-related SMM, operation 7 is the one with

the highest frequency.

5.3.2. Landing profile of unstable approach

This section presents the airspeed and altitude profile in an unstable approach. The overall flow is presented in **Fig. 5-5**. The altitude profile indicates a significant change as the remaining track miles decrease. For the state under 50 or 30 Nm STAR, the upper quartile was approximately 1000 feet higher than the STAR requirements, whereas the altitude deviation increased to between 2000 and 3000 feet when the remaining track miles were 15 or 10 Nm. Similarly, the airspeed profile indicates that the range of deviation gradually increases as the aircraft approaches. In the scenario at 10 Nm, the airspeed deviation was up to 50 knots faster than the STAR requirements.

Fig. 5-5 Landing profile of unstable approach

5.3.3. Model validation

EFA is conducted to examine whether the simulation results had a structural relation similar to the experts' experience. Among three of the scenarios included, the scenario in the terminal area (30–15 Nm) had results similar to those of the survey for both the extracted factors and their composition. As shown in **Table 5-7**, three factors were extracted: 1) failure to intercept landing risks, 2) passive information

dissemination, and 3) incompatible work results among team members. In all, for both of the simulation and survey, factors 1 and 2 are the two major factors extracted with relatively higher loading of variance. For the survey result, factor 1 possesses the highest variance loading (23.738 %). While, as for the simulation result, factor 2 contributes to the highest loading of variance (30.742 %)

For factor 1, the major overlapping items were operations 3, 5, 6, 7 and 8, operations 5, 6 and 7 refer to failure to timely intercept potential landing risks. For factor 2, the major overlapping items were operations 5, 8, 9, and 10. The combination of operation 8, 9 and 10 causes passive information dissemination from ATCOs, because of which pilots encounter difficulty in adapting to air space changes. While, for the landing between 30 and 15 Nm, operations 1 and 7 also had significant loading for factor 2. Finally, for factor 3, referring to incompatible work results among team members, the overlapping items were operations 1, 2, 4 and 7, indicating that operators had difficulty in executing their tasks so as to meet team members' expectations.

Table 5-7. Comparison of structural relations between survey and simulation results.

Data set		Factor 1 The failure of intercepting landing risks	Factor 2 Passive information dissemination	Factor 3 Incompatible working results between team members
Survey result	Loading (% of variance)	23.738 %	19.390 %	17.694 %
	Op_1			0.712
	Op_2			0.806
	Op_3	0.827		
	Op_4	0.402	0.353	0.429
	Op_5	0.534	0.545	
	Op_6	0.853		
	Op_7	0.636		0.558
	Op_8	0.260	0.457	
	Op_9		0.686	0.329
	Op_10		0.898	
Scenario within 30nm	Loading (% of variance)	16.625%	30.742%	16.321%
	Op_1		0.755	-0.272
	Op_2			0.878
	Op_3	0.881		
	Op_4			0.825
	Op_5	0.248	0.630	
	Op_6	0.578	0.283	
	Op_7	0.350	0.777	0.202
	Op_8	0.432	0.625	
	Op_9	0.337	0.637	
	Op_10		0.782	

* Items with the value below 0.2 were not considered.

* Overlapping items are shown in bold font.

5.4 Discussion

According to **Table 5-5**, operational disconnects occurred increases significantly as an aircraft approaching. A possible reason for this is the frequent changes in flight state due to increasing time pressure and the limited airspace in the terminal area, which intensifies the evolution of scenarios. This combination reduces safety margins available, making the system be subject to system errors. Accordingly, for the landing process in the outer area (100–50 Nm), the sufficient time and space make it easier for operators to react promptly to contingencies. Thus, the occurrence of both task and team-related disconnects are relatively low. By contrast, in scenarios close to the terminal area (30–15 Nm), the operational disconnect frequency was significantly higher. Particularly, the team-related operational disconnects are frequent. It reflects that the team-related SMM in the scenarios under the terminal area is an urgent issue to be examined.

To achieve a more comprehensive examination, the context of an unstable approach can also be approached by the pattern of operational disconnects. In the outer area (100 to 50 Nm), the operational disconnects in task-related SMM are more frequent than most of team-related SMM's (other than operation 9 and 10). Generally, the relatively sufficient airspace and time may make both pilots and ATCOs prefer non-routine operations to optimize resource use. However, the operational disconnects in

task-related SMM is a major challenge for this, causing incompatible working results in implicit interaction. Even worse, operators may even compromise the team members' resource for optimizing their performance [42]. For example, ATCOs may request pilots to follow unsuitable instructions to expedite the landing, causing pilots hard to follow the STARs (operation 3 and 4). Similarly, pilots may attempt an efficient approach to save fuel and thus not strictly follow ATCO instructions (operation 1), which impacts the separation of succeeding air traffic flow [12, 42]. To eliminate task-related operational disconnects, proper monitoring of the system state is important, which enables operators to actively consider team members' requirements [45]. However, the associated possible information disconnects present a challenge as mentioned. The implementation of different information systems between parties limits to the information available to an operator for system monitoring, which is a common issue encountered in MTSs. Thus, the inclusion of extra mutual-information between parties for a better implicit interaction can be a key to eliminate the onset of system risks.

In the terminal area (30–15 Nm), the time pressure and limited space cause rapid evolution of scenarios, making operational disconnects occurred soar. Specifically, frequent operational disconnects in team-related SMM reflects the challenges in a team's purposeful risk detection and mitigation. This issue can be approached by two

aspects. One is the passive information dissemination from ATCOs (operation 8, 9 and 10), another is the late interaction for correcting landing state (operation 5, 6 and 7). First, the passive information dissemination from ATCOs further deteriorates the negative effect of informational disconnects mentioned in the previous paragraph, making pilots unable to react to the urgent issues in a timely manner. In this case, it can be ascribed to the limitation of 1 to 1 radio channel, which deteriorates the efficiency of conducting frequent interactions with pilots. Furthermore, sometimes, additional external factors enter into play, including unexpected weather patches, the landing clearance of preceding aircraft, or runway changes, all of which heighten the necessity for active information dissemination. Thus, the results from operation 8, 9 and 10 cause a high frequency of operation 5, 6 and 7. Late provision of corrective instructions from ATCOs may make pilots miss the window to address improper landing state (Operation 7). To prevent this, pilots are also required to actively engage ATCOs for assistance. However, the high frequency of operation 5 and 6 reflects the challenges in this issue. Pilots' overconfidence and possible continuation bias are identified as factors for passive coordination in such circumstances [25, 113].

The landing profile in **Fig. 5-5** provides an overall illustration of how unstable approach occurs. The degree of deviation in both airspeed and altitude gradually increases as the aircraft approaches. This pattern highlights the snowball effect in an

unstable approach. As the aircraft approaches, it becomes increasingly more challenging for a team to rectify the deviation, given the limited time and space. According to literature, an unstable approach is often accompanied by excessive altitude or airspeed [9, 113]. As shown in **Fig. 5-5**, the area between the upper quartile and median in the altitude profile is significantly larger than the corresponding area in the airspeed profile, indicating that the degree of airspeed deviation in the final landing phase is smaller than that of altitude deviation, as a result of pilots' landing technique. Pilots in a deviant landing profile flexibly deploy the speed brake, flaps, or landing gear to offset excessive energy and focus primarily on offsetting airspeed to increase the overall air drag, thus increasing the efficiency of energy management [48].

As for the model validation, EFA is used to test whether the model could produce an explanation similar to that of expert experience, with several notable findings. First, three similar factors could be extracted from both data sets, demonstrating that the model provided a satisfactory explanation of system performance. Passive information dissemination (factor 2) and failure to intercept landing risks in a timely manner (factor 1) were the two most significant factors extracted, with a sum of variance of more than 40% in both data sets. Accordingly, consistent team-related SMM is a key to prevent unstable approach from occurring. Moreover, incompatible work results among team members (factor 3) is another issue that should be considered, explaining 17% of the

variance in both data sets and further emphasizing the necessity of implicit interaction and proper task-related SMM [42, 47, 112]. The reduction of system risks due to incompatible working results can relief the demands for coming explicit interaction. Furthermore, a major difference between the simulation and the survey cannot be ignored. As shown in **Table 5-7**, the survey results indicated that factor 1 was the dominant factor, whereas, in the simulation, the dominant factor was factor 2. This might be explained by differences in factor composition. Operations 1 and 7 had significant loading in factor 2, indicating that late intervention with corrective instructions (Operation 7) and inaccurate execution of received instructions (Operation 1) are also involved in the effect of factor 2. This also suggests that the importance of information dissemination has a more than expected significant impact on both task and team-related SMM.

In general, the results provide insightful knowledge for future research. First of all, the improvement of information transparency for a more repaid and immediate information dissemination is the key. Particularly, the identification of the information to be shared in the future system and how the MMDs are accordingly eliminated deserve further attention. Furthermore, this work also has the potentials for developing a landing-risk forecasting system. Current research utilized three parameters in the final phase of a landing, including touchdown distance, touchdown vertical acceleration and

touchdown pitch angle to evaluate and predict the landing risks of a single flight [16].

In this research, the data input covers both pilots and ATCOs from IAF to FAF and provides opportunities to intercept an unstable approach in an early stage.

5.5 Summary

In this research, FETC is implemented to examine an unstable approach from the perspective of team interactions and possible MMDs. With the implementation of ABM, the context of an unstable approach is further examined for identifying the direction of future improvements. The main contributions of this research can be summarized as follows:

Theoretical contribution. FETC was proposed to explain how MMDs get involved in the evolving team cognition. The faulty interaction results (implicit and explicit) due to mental model disconnects reflects how a team makes mistakes during interactions, causing an accident. Therefore, a researcher is able to identify the root causes to be considered for better accident analysis and prevention. Furthermore, the combination of FETC and ABM also provides an insightful approach to examine operators' cognitive process in an MTS. It helps to study a team's performance scenario by scenario, which depicts a more comprehensive understanding of the context of an accident.

Practical value. The results of this research help to achieve practical

improvements for a landing system. The negative effect of mental model disconnects under different scenarios should be mitigated respectively. For the landing at the outer area, the information transparency has to be improved for better mutual monitoring, facilitating the quality of implicit interaction. Furthermore, it also decreases the risks accumulated, relieving the coming reactive actions needed. As for the landing process around the terminal area, the execution of timely team coordination for intercepting errors accumulated is crucial. For future study, the way of communication should be improved for more efficient and rapid information dissemination as the conditions changing. It helps both parties to comprehend the current risks in a consistent manner, initiating required actions to eliminate the landing risks.

Despite these contributions, some limitations of this research should be further addressed. Obtaining a direct, realistic data set for the examined interaction conflicts was difficult, which would eventually affect simulation results and their validation. Therefore, developing an appropriate reporting system to collect reliable data is essential to facilitate the implementation of this approach in reality. In general, the results of this chapter provide comprehensive insights for the occurrence of an unstable approach, which suggests future improvements regarding information transparency. Further research is accordingly conducted to investigate how a landing system is implemented.

6 . Toward better information transparency in a landing system

With the ever-increasing demands of air traffic flow management, the landing system requires fundamental improvements to meet future needs. For the current landing system, information gaps between parties (i.e., pilots and ATCOs) cause issues regarding information transparency, which hinder a system's risk detection and mitigation. Therefore, efficient implementation of data links can promise better information transparency by facilitating the execution of both implicit and explicit interactions between parties to predictively adapt to changing conditions. To achieve this, this research proposes a smart interaction system based on two agent-based models and further compare them to examine the improvements in a system's reliability and efficiency. Results show that the sharing of critical information considerably reduces the reactive actions needed to cope with congestions and system errors. Moreover, the efficiency of resource utilization is improved without causing a significant delay and hence characterizes a more reliable and efficient landing system.

6.1 Introduction

From the results presented in Chapter 5, research issues regarding information

transparency are pinpointed. Specifically, the issues of passive information dissemination and late initiation of corrective interaction are critical factors in an unstable approach. As discussed above, the development of team cognition requires a team to disseminate the information mutually to update and synchronize operators' SMMs [22, 44, 60]. Accordingly, the dissemination of critical information can be the onset of effective interaction. Therefore, for the result presented in Chapter 5 (See **Table 5-7**), the passive information dissemination from ATCOs may be a cause of late intervention for landing instability. Similarly, incompatible working results between operators are also related to the scenarios of unstable approach.

Nevertheless, in the near future, the implementation of data links can be a solution for this challenge. Efficient information dissemination with fewer resources enables data-link technology to replace traditional voice communication [30, 129, 130]. In fact, the importance of information transparency has been emphasized by relevant research. Whether a distributed team can receive consistent information regarding the changes of the big picture is vital for a reliable system performance [45, 124, 125]. However, little research has investigated the potential of information transparency from the perspective of prevention of MMDs. In a nutshell, better information transparency due to the implementation of data-link technology not only eliminates informational disconnects but also mitigates possible operational disconnects in both implicit and explicit

interactions. Furthermore, data link achieves immediate information dissemination, which grants stakeholders more time and flexibility for the operations. As a matter of fact, it also shares a similar idea with the concept of free flight. Pilots will have the freedom to determine their own flight state without affecting the overall system performance [128, 131].

This chapter aims to examine how better information transparency improves the landing system from the perspective of team interaction. How operators' action and strategy change are investigated and modeled. By implementing ABM, the current and improved landing system is simulated to examine the exact benefits of information transparency.

6.2 Related work

This section provides a comprehensive review of possible benefits of information transparency from the view of possible facilitation in both implicit and explicit interactions. Furthermore, some additional information is included for a more comprehensive ABM.

6.2.1. Information transparency in implicit and explicit interactions

To explain operators' performance in a system, the rotation between proactive and reactive actions is a straightforward perspective. Proactive actions help to manage the

potential risks and workload in advance, whereas reactive interaction is executed to ensure everything is back to normalcy [5, 132]. Although reactive action is a “safety net” to prevent system errors from evolving into adverse events, high demands of reactive actions still reflect an unreliable system prone to errors.

Based on the proposed role-specific SMMs, at least one acceptable solution can be provided for satisfying team members’ expectations based on proper and consistent common goals. In the case of a distributed system, defective proactive interaction can be a source of system errors. Some proactive actions only emphasize individual situation awareness (SA) without considering a team’s SMMs, which causes operational disconnects. What is worse, one party may compromise team members’ resource for optimizing their own performance [42]. Take the result obtained in Chapter 4 as an example; ATCOs may expedite the landing process by canceling the speed restriction of STAR. It can be treated as a proactive action from the ATCO’s perspective, which enables the ATCO to manage the air traffic flow in advance and prevent possible congestion. However, this operation may reduce pilots’ available time to operate the aircraft, causing potential landing risks [12].

To avoid such requirement contradiction during both implicit and explicit interactions, the monitoring of the overall system state is vital, which heavily relies on a system’s information transparency between parties. One has to understand the

changes in the state of overall system before anticipating the system needs or initiating corrective actions [42, 45]. However, the information gaps due to the diverse information system applied and the one-to-one radio channel are the major challenging. The information gaps may result in inconsistent evaluative criteria, which impair predictive adaption. The finding of Chapter 5 also strengthens this issue.

To address this issue, a system's dynamic information is an aspect to be shared, including current goals, cognitive workload, or noise levels [45]. To satisfy the requirements of system state monitoring, research indicated that the elimination of discrepancy between the machine model and users' mental model is key for tracking the system state while interacting with the machine and making timely error corrections [133]. Accordingly, among all the items mentioned, the sharing of current goals is a practical option that can be implemented. Specifically, from the perspective of SA, a party's finalized goals are subject to the cues perceived from environment [55]. Sharing the critical information applied in SA can be a critical foundation for initiating immediate and proper interaction, enabling the party to roughly extrapolate team members' goals. In fact, some experienced operators are able to conduct proper proactive actions with limited information. For example, experienced captains are able to make use of the information from a traffic collision avoidance system (TCAS) or the communication between ATCOs and other pilots to deduct the state of air traffic flow

and ATCO's possible goals [42].

To conclude, poor role-specific SMMs and insufficient information transparency can make the proactive actions taken as a source of system errors. The contradiction of requirements makes a system prone to operational disconnects, requiring frequent reactive actions to mitigate the generated system risks. To mitigate this issue, sharing of the information utilized in SA allows one to dynamically monitor team members' goals, avoiding possible evaluative and operational disconnects.

6.2.2. *ABM*

In this chapter, ABM is also applied to examine how the changes in micro-level behavior (information transparency during coordination) affect the emerging system performance (overall landing system) [94, 95]. By definition, the agents in ABM refer to the autonomous entities that act according to their own interests and rules. In this thesis, the agent is defined as the team comprising pilots and ATCOs, determining an aircraft's operations. Thus, an aircraft can be the presentation of agent that acts according to the results of interactions.

To conduct agent-based simulation, the properties and requirements of such a critical system should be determined. Based on the taxonomy proposed by Rushby [134], the complex interaction and tight coupling characterize a landing system. In short, most of the tasks are collaboratively achieved by the multi-agent interaction regulated

and required to produce the outputs before deadline with limited time and resources. The interaction restrictions due to this property ensure the system's dependability. Accordingly, relevant research examined the multi-agent interaction of a landing system, emphasizing on determining how the system functions and goals (the higher abstract level) are fulfilled by agents' actions and corresponding interactions (the lower abstract level). By doing this, the issues at the lower abstract level such as miscommunication or the changes in the automation level can be introduced to examine the emerging system performance [135, 136]. Nevertheless, considering the increasing demands of air traffic, data link technology, and the possibility of free flight, a more flexible yet reliable landing system is promising to mitigate the restrictions of complex interaction and resource utilization.

For a better illustration regarding how a system is improved, **Fig. 6-1** demonstrates the structural difference between the goal-oriented system [135, 136] and the proposed system with better information transparency. For the current goal-oriented system, operators utilize the respective resource pool to conduct both taskwork and teamwork. Taskwork denotes the required performance to be accomplished by an operator, whereas teamwork denotes the coordination needed for changing the current task focuses [45, 135]. In this system, factors such as underlying information gaps or MMDs can jeopardize the quality of system goals formed. Furthermore, the potential

operational disconnects between parties due to defective proactive actions may lead to faulty aircraft maneuver, which affects the overall air traffic flow. As for the improved system, the sharing of critical information helps operators achieve a more consistent understanding regarding the changes in the system state and team members' goals. Accordingly, instead of passively receiving critical information from team members, operators can actively adjust the taskwork and initiate coordination with teamwork in a proactive manner, which helps prevent possible errors. Furthermore, one can also optimize the respective resource without affecting team members, thereby maintaining the quality of system goals.

Fig. 6-1 Comparison of system structures

To test the specific benefits from information transparency, the reliability and efficiency are included. For the system reliability, the frequency of the reactive actions executed is focused. Less reactive actions reflect the reduction in system errors. Four

types of reactive actions are commonly executed to solve urgent risks that occur, namely conflict resolution, late descent, go-around, and hovering over the outer area [5, 12, 48, 113]. By contrast, the system efficiency is examined from the perspective of resource utilization. The reactive actions executed, which are listed above, may lead to additional consumption of time and resources. In this thesis, three items are considered: the extra miles traveled by the aircraft, fuel burnt, and time needed for the aircraft to be transferred. Details are presented in **Table 6-1**.

Table 6-1. System indexes of reliability and efficiency

System reliability	
Items	Description
Conflict resolution	When the separation between two aircraft is less than 3 Nm, the aircraft will be vectored away by ATCOs to avoid a possible collision in the air.
Late descent	Pilots are asked to fly at a higher altitude to maintain the vertical separation. This operation is particularly common when the segment between intermediate approach fix (IAF) and final approach fix (FAF) is congested.
Go-around	When the aircraft is not able to satisfy the stable approach criteria before reaching the decision height (1000 ft), the operation of go-around is crucial for pilots to stabilize the aircraft.
Hovering over the outer area	When the segment between IF and FAF is congested, the aircraft in the outer area is asked to hover around, avoiding further congestion.
System efficiency	
Extra miles traveled	Generally, the path traveled is based on the flight plan. However, in congested or conflicting scenarios, pilots may be detoured to prevent further risks regarding insufficient separation.
Fuel burnt	More distance traveled represents more fuel burnt. The fuel

	consumed is subject to the current altitude or deceleration rate. Specifically, the aircraft at a low altitude burns relatively more fuels due to higher air density.
Time required for being transferred	Punctuality of a landing system is critical. The reactive actions such as conflict resolution or go-around are factors that cause delays in schedules.

To conclude, ABM is a suitable approach to study the contribution of better information transparency. The team with better information transparency is capable of conducting proper proactive actions to prevent possible operational disconnects. To achieve a more comprehensive understanding, the system's reliability and efficiency are considered in the ABM.

6.2.3. Summary

To avoid defective team cognition, it is crucial to mitigate the underlying MMDs. Better information transparency helps to eliminate informational disconnects, decreasing the occurrence of evaluative and operational disconnects. Furthermore, it facilitates the quality of proactive actions for a team to predictively manage upcoming changes and reduce possible conflicts between parties. Sharing critical information in level 1 SA can be a leverage point in sharing stakeholders' dynamic goal changes. In the developed agent-based model, the system's reliability and efficiency are included for more comprehensive examination. Hence, the research hypotheses in this simulation are stated as follows:

- *H1: With better information transparency, proactive actions reduce the need for*

reactive actions (system reliability).

- *H2: With better information transparency, proactive actions facilitate the efficiency of resource utilization (system efficiency).*

6.3 Methodology

6.3.1. Environment setting

The ABM is modeled based on the simplified approaching area of Changi airport in Singapore. The radar map and the STAR are shown in **Fig. 6-1**. Aircraft will approach the terminal area from five different STARs indicated by triangles. Aircraft are set as agents which act based on the interactions between parties. The radar map is divided into three sections to cover the airspace. Section A refers to the outer area where the aircraft start to approach. Section B is the transition between Section A and the inner terminal area, section C. Two ABMs are developed accordingly. One is to simulate the current state of the landing system as a reference, and the other model is to simulate how information transparency benefits the system performance. Ultimately, the respective results are compared to identify the improvements in a system's reliability and efficiency.

the improved system with better information transparency, the proactive actions are modeled based on the requirements of role specific SMM, which aims to achieve a system's coordinability and consistency instead of optimizing one's own benefits.

Table 6-2. General operations in the modeling

Items	System conditions	Operation description
Follow STARs	Conditions: Congestion in section C	Under congested scenarios, pilots are requested to follow STARs to minimize uncertainty. The STARs determined is shown in Fig. 6-2 .
	Location: Any	
Hovering around at the outer area	Conditions: Congestion in section C	When the air traffic flow is congested around the terminal area, all the aircraft at the outer area are requested to hover around, creating buffers for ATCOs to adjust the air traffic flow.
	Location: Section A	
Late descent	Conditions: Congestion in section C	When the air traffic flow is congested around the terminal area, pilots are asked to maintain a higher altitude for the vertical separation.
	Location: Section C	
Conflict resolution	Conditions: The insufficient separation between aircraft	When the separation is insufficient, the succeeding aircraft is asked to decelerate (5 Nm to 3 Nm) or be vectored out to avoid conflict in the air (less than 3 Nm).
	Location: Any	
Go-around	Conditions: Unstable approach <i>or</i> late landing clearance from the preceding aircraft	When the landing of the preceding aircraft is not cleared or the aircraft do not satisfy the stable approach criteria, pilots are requested to vector out to re-approach.
	Location: Section C: 10 Nm	

Table 6-3. Proactive operations modeled in respective ABMs

The defective proactive operations in the current landing system		
Items	System conditions	Operation description

High-speed clearance	Conditions: Light air traffic flow	To fully utilize the empty airspace, ATCOs expedite the landing process by canceling the speed restriction [12, 43].
	Location: Section A / Section B	
Efficient approach	Conditions: Light air traffic flow	To preserve the fuels burnt, some pilots would like to fly slightly higher and slower. However, it may affect the succeeding flow. In addition, higher altitude may also increase the possibility of an unstable approach [12, 48].
	Location: Section A / Section B	

Proactive interaction in the landing system with better information transparency

Hover at the outer area	Conditions: Congestion in section C	Information shared from Pilots Fuels/type of aircraft
	Location: Section A	Operators: ATCOs ATCOs will ask the aircraft which just entered the airspace to hover around at higher altitude to decrease the fuels burnt in vain [42].
Slower approach	Conditions: Congestion in section C	Information shared from ATCOs The air traffic flow in section C
	Location: Section A / Section B	Operators: Pilots This operation is not formally regulated, while, the slower approach in section A and B may help to create buffers for ATCOs to mitigate congestion. In section A, only the aircraft which have finished the descend will conduct a slower approach to save fuels.
Efficient approach	Conditions: Light traffic and sufficient separation.	Information shared from ATCOs Surrounding air traffic flow / Aircraft's weight
	Location: Section A	Operators: Pilots The first aircraft in the queue can conduct an efficient approach without affecting the air traffic flow behind.

High-speed clearance	Conditions: Light traffic and sufficient separation.	Information shared from Pilots Aircraft's weight / the deceleration and descent rate.
	Location: Section A	Operators: ATCOs The high-speed clearance given is based on an aircraft's weight to prevent concerns regarding separation and landing stability [42].
Expedite descent	Conditions: Higher altitude and the first aircraft in a queue	Information shared from ATCOs Surrounding air traffic flow
	Location: Section C	Operators: Pilots For experience captains, the landing configuration is deployed flexibly to expedite descent [42, 48]. It achieves a higher rate of deceleration and descent to ensure landing stability.

In order to test how information transparency benefits a landing system, the system's reliability and efficiency are included in the modeling. Four reactive actions conducted are shown in **Table 6-2** above, and the frequency is recorded respectively to examine a system's reliability. As for the system's efficiency, it is approached by operators' resource utilization. Three items are considered, including the extra miles traveled, the fuels burnt and the time needed for being transferred, where details are shown in **Table 6-4**.

Table 6-4. Indexes for system efficiency

Items	Description
Extra miles traveled	When the aircraft are asked to be vectored out or hovering around, the extra track miles traveled are recorded.
The fuels burnt	<p>The fuels consumption is fewer at higher altitude due to the lower air density. Furthermore, weight is also factors to be considered.</p> $\text{Fuel} \propto \rho \times m$ <p>To simplify the calculation, the aircraft's size and engine design are set to be the same. The fuels burnt is proportional to the current air density (ρ) times weight (m). In this work, the weight of light aircraft is 1, while heavy aircraft is 1.5.</p>
The time needed for being transferred	When an aircraft is transferred to the tower at the end of the flight path modeled, the total time spent is recorded.

In sum, two types of team logic are presented below to show the structural difference between current and improved landing system (See **Fig. 6-3** and **Fig. 6-4**).

In general, the ABMs simulate the rotation between regular and the near-miss scenarios. In the latter scenario, a team has to conduct reactive actions to mitigate the emerging system risks immediately to prevent adverse events. The actions underlined denotes to the actions the agent (aircraft) ultimately conducted. On the other hand, the actions without underline and the thin-line arrow represents the decision flow which determines a certain action to be executed. For example, ATCOs will provides instructions via teamwork based on the taskwork, air traffic flow management. Then, pilots conduct the instructions to maneuver the aircraft. **Fig. 6-3** illustrates the team logic of the current landing. Operators can only access the respective information pool; thus, information

gaps and possible operational gaps may come into play, affecting the system's performance. On the other hand, **Fig. 6-4** demonstrates the improved system which shares some critical information for a team to mutually monitor the changing conditions and goals. The operations based on better information transparency are labeled with bold outlines and fonts. The corresponding proactive actions enables operator to predictively adjust the performance and initiate coordination required to avoid near-miss scenarios as possible.

Fig. 6-3 Team logic in current landing system

Fig. 6-4 Team logic in a system with improved information transparency

6.3.3. Algorithm structure presentation

Based on the **Fig. 6-5** and **Fig. 6-6**, the overall mechanism of ABM developed is illustrated below. The items labeled with the dash-line rectangle denote the reactive actions conducted, while, the operations with bold font are the operations modified in the improved system in **Fig. 6-6**. For both of the ABMs, four categories of reactive actions are modeled in the respective section to cope with near-miss scenarios. In general, the conflict resolution is prior to other three reactive actions to prevent collision in the air. Go-around aims to ensure an aircraft satisfy stable approach criteria, while both hovering around, and late descent are conducted to rearrange the congested air

traffic flow.

Fig. 6-5 displays the logic for the current landing system. As **Table 6.3** presented, due to insufficient information transparency, the execution of high-speed-clearance and efficient approach conducted in section A and B may not be able to benefit the system's performance as expected, even causing potential system risks. Furthermore, the emerging system risks may be amplified and trigger chain reaction to cause congestion in section C and near-miss scenarios. On the other hand, **Fig. 6-6** illustrates the system with better information transparency. The operations based on better information transparency are labeled with bold outline and fonts. In this model, both high-speed-clearance and efficient approach can be conducted in ways which consider team members' requirements, which reduces possible congestion in section C. In addition, with better information transparency, expedite descent, slower approach and hovering at higher altitude are accordingly added for operators to collaboratively create buffers where needed for avoiding the possible near-miss scenarios.

Fig. 6-5 ABM logic for the current system

Fig. 6-6 ABM logic for the system with improved information transparency

6.4 System implementation

6.4.1. Algorithm development

In this research, NetLogo[®] is the software mainly applied. The environment developed is illustrated in **Fig. 6-7**. The stochasticity of the landing system is also considered for a more realistic simulation. Firstly, both light and heavy weight of aircraft are introduced. The attributes like deceleration rate, and fuels consumption rate are set differently to simulate the system complexity due to weight difference. Secondly, an aircraft will approach from one of the five entry points randomly. Meanwhile, due to the software's limitations, the airspace is set to accommodate a maximum of 15 aircraft. The simulation stops when the sum of landing is 1000 for proper convergence. Generally, separation maintenance is the priority. The aircraft can only keep approaching when the issue of collision is cleared. Aircraft will approach the terminal area based on the actions modeled and exit the loop after being transferred to tower, controllers. Simultaneously, for each aircraft, the utilization of resource and the frequency of the reactive actions are recorded and output. The pseudo code of the system modeling is presented below. Furthermore, **Appendix 4** provides a more comprehensive overview, comprising the parameters defined, attributes and the codes developed for agents' actions.

Fig. 6-7 Environment developed in NetLogo®

Algorithm 1 simulates the current landing system. In section A, the number of aircraft in section C differentiates light-traffic or congested scenarios. The scenarios with more than 5 aircraft in section C denotes a congested scenario. In such a case, aircraft in section A will be asked to hover around to prevent further congestion. The aircraft is cleared to approach when the congestion in section C has been mitigated (no more than 2 aircraft). On the other hand, to fully utilize the light-traffic airspace, the first aircraft in the approaching queue in section A is issued to conduct high-speed clearance, while the rest of aircraft in the queue will follow STARs. In this case, 30 % of aircraft are set to conduct an efficient approach to simulate the stochasticity due to SMM inconsistency. In section B, the mechanism is similar to section A's, however, under congested scenarios, aircraft are kept vectored in by following STARs instead of

hovering around. In section C, under light-traffic scenarios, aircraft are asked to strictly follow the STARs to prevent unstable approach. Under the congested scenario, the succeeding stream of aircraft is requested to conduct late descent to maintain vertical separation. Lastly, if an aircraft satisfies the stable approach criteria at 10 Nm to finals, the aircraft is transferred to tower. Otherwise, a go-around is initiated to stabilize the aircraft.

Algorithm 1. ABM for current landing system

Start

While number-of-aircraft-transferred < 1000

If sum-of-aircraft <= 15 [**Ask** Aircraft **Do** enter-airspace **From** **Random** entry-points]

Ask aircraft

Do record-time

Check separation-with-preceding-aircraft

If separation-with-preceding aircraft <= 3 Nm [**Do** conflict-resolution]

Else [**Do** keep-approaching]

Function keep-approaching {

Check section

If in sectionA/ *heavy-traffic-mode is used to determine the scenarios (congested or light-traffic) applied.*

Check number-of-aircraft-in-sectionC

If number-of-aircraft-in-sectionC >=5 [**Set** heavy-traffic-mode **on**]

If (number-of-aircraft-in-sectionC <=2 **and** heavy-traffic-mode **on**) [**Set** heavy-traffic-mode **off**] / *it makes the heavy-traffic-mode can be off when the congestion is mitigated.*

If heavy-traffic-mode **on** [**Do** hovering-around]

If heavy-traffic-mode **off** [

Check preceding-aircraft [

If preceding-aircraft = **none** [**Do** High-speed-clearance-current] / 20 knots faster

else [**Random** 70% **Do** Follow-STARs, 30% **Do** Efficient-approach]]] / 10 knots slower and 1000 ft higher to achieve a gradual approach.

```

If in sectionB
    Check number-of-aircraft-in-sectionC
    If number-of-aircraft-in-sectionC >=5 [Do Follow-STARs]
    else [Check preceding-aircraft [
        If preceding-aircraft = none [Do High-speed-clearance-current]
        else [Random 70% Do Follow-STARs, 30% Do Efficient-approach]]]
    If in sectionC(35-10Nm)
        Check number-of-aircraft-in-sectionC
        If number-of-aircraft-in-sectionC >=5 [
            Check surrounding-aircraft [
                If preceding-aircraft = none [Do Follow-STARs]
                else [ Do late-descent]]] / 1000 ft higher than STARs
            else [Do Follow-STARs]
        If in sectionC(10Nm-to-finals)
            Check flight-state
            If flight-state = (3000ft/170kt) [Do transfer-to-tower Do update-number-
            landing Output Record-performance]
            else [Do go-around]
        }
    End while

```

Algorithm 2 shows the logic of the landing system with better information transparency. The script describing the improved operations is labeled and underlined. The pre-setting is the same as **Algorithm 1**'s for a more accurate comparison. For the approaching procedure in section A, similarly, the number of aircraft in section C is set as the threshold to differentiate congested or light-traffic scenario. In congested scenarios, for the aircraft with a higher altitude than STARs requirement, they are asked to hover around at higher altitude to save fuels. For all the other aircraft which already finish the descend, they will commence on a slower approach to create buffers for ATCOs to manage congestion. Meanwhile, for the light-traffic scenarios, high-speed

clearance is issued with the considerations of aircraft's weight difference. Furthermore, the efficient approach is only conducted when the succeeding aircraft is light to prevent the rear aircraft from catching up. In section B, the procedures are similar to section A. However, the hovering around is no longer applicable due to limited airspace. In section C, under both circumstances (congested and light-traffic), the first aircraft in the queue is cleared to conduct expedite descent to expedite the air traffic flow and mitigate the congestion behind. As for other aircraft in the queue, late descent is issued to ensure vertical separation under congested scenarios. Meanwhile, under light-traffic scenarios, pilots are requested to follow the STARs to ensure landing stability. Ultimately, an aircraft is transferred to the tower upon the stable approach criteria is satisfied.

Algorithm 2. ABM for the landing system with better information transparency

Start

While number-of-aircraft-transferred < 1000

If sum-of-aircraft <= 15 [**Ask** Aircraft **Do** enter-airspace **From** **Random** entry-points]

Do Aircraft-enter

Ask aircraft

Do record-time

Check separation-with-preceding aircraft

If separation-with-preceding aircraft <= 3 Nm [**Do** conflict-resolution]

else [**Do** keep-approaching]

Function keep-approaching {

Check section

If in sectionA / *heavy-traffic-mode is used to determine the scenarios (congested or light-traffic) applied.*

Check number-of-aircraft-in-sectionC

If number-of-aircraft-in-sectionC >=5 [**Set** heavy-traffic-mode **on**]

If (number-of-aircraft-in-sectionC <=2 **and** heavy-traffic-mode **on**) [**Set**

heavy-traffic-mode **off**] / it makes the heavy-traffic-mode can be off when the congestion is mitigated.

If heavy-traffic-mode **on** [

Check altitude [

> **If** altitude > STARs-requirement [**Do** hover-at-high-altitude]

> **else** [**do** slower-approach]] / 10 knots slower than STARs

If heavy-traffic-mode **off** [

Check preceding-aircraft [

> **If** preceding-aircraft = **none** [**Do** High-speed-clearance-improved] / *light aircraft:* > 20 knots faster, heavy aircraft is 10 knots faster

> **else** [**Check** Surrounding-aircraft(location&types)]

if (the-separation-of-succeeding-aircraft >= 10 Nm **and** succeeding-aircraft-is-light) [**Do** efficient-approach]

else [**Do** Follow-STARs]]]

If in sectionB

Check number-of-aircraft-in-sectionC

> **If** number-of-aircraft-in-sectionC >=5 [**Do** Slower-approach]

> **else** [**Check** preceding-aircraft [

> **If** preceding-aircraft = **none** [**Do** High-speed-clearance-improved]

else [**Check** Surrounding-aircraft(location&types)]

if (the-separation-of-succeeding-aircraft >= 10 Nm **and** succeeding-aircraft-is-light) [**Do** efficient-approach]

else [**Do** Follow-STARs]]]

If in sectionC(35-10Nm)

Check number-of-aircraft-in-sectionC

If number-of-aircraft-in-sectionC >=5 [

Check surrounding-aircraft [

If preceding-aircraft = **none** [**Do** Expedite-descent] / *descent rate is set to be 4500ft / 10 Nm (Normally is 3000ft / 10Nm)*

else [**Do** late-descent]]]

else [

Check surrounding-aircraft [

If preceding-aircraft = **none** [**Do** Expedite-descent]

else [**Do** Follow-STARs]]]

If in sectionC(10Nm-to-finals)

Check flight-state

If flight-state = (3000ft/170kt) [**Do** transfer-to-tower **Do** update-number-landing **Output** Record-performance]

```
        else [Do go-around]
    }
End while
```

6.4.2. Sensitivity test

A sensitivity test was conducted to examine how the simulation outputs reflect the changes of parameters. A robust ABM should not be subject to the change of a single parameter. In order to conduct a relatively reasonable test, the parameters to be tested should be carefully considered. For a landing system, most of the attributes, like airspeed limitation, STAR settings or separation constraints, are carefully designed. Arbitrary changes may cause simulation breakdown and invalid outcomes. Therefore, in the case herein, deceleration and descent rate was chosen to be tested. As the results of Chapter 4 show, both parties may execute the operations based on their own benefits.

The range of the parameters was set to be a range between + 50 % and -50% of the nominal value. The nominal value in the simulation was by the rule of thumb in a landing. Specifically, based on the “rule of three” in aviation, a pilot can conduct a proper descend of 3000 ft with 10 Nm. Furthermore, to lose 10 knots of airspeed, at least 1 Nm is required. Thus, in the sensitivity test, the descent in 10 Nm can be within 4500 ft ~ 1500 ft, which simulates the deviation due to operation disconnects.

In order to test the robustness of the ABM developed in a more comprehensive manner, the sensitivity test based on model-based output variance decomposition (See

Section 2.7) was suitable. However, no suitable regression function in relation to the parameters to be tested was found. Relevant details are shown in **Appendix 5**. Therefore, the test based on OFAT was adopted instead.

As for the OFAT testing, a normal scenario was set to be a reference by fixing both deceleration and descent rate as nominal values. Then, for the respective parameters to be tested, two scenarios were set by adjusting the parameters either + 50 % or -50% of the nominal values. Accordingly, four scenarios were created (two parameters with two levels). As for the items of simulation outcome, due to the limitation of NetLogo® and insufficient knowledge regarding the fuel consumption rate and different types of aircraft. Therefore, simulation outcomes exclude the calculation of the fuels consumed. Several independent *t*-tests were performed to examine statistical differences under the 95% confidence interval, with significance indicated by a *p*-value of <0.05. The results are listed in **Table 6-5**, wherein no parameter is predominant, showing descent robustness of the algorithms developed.

Table 6-5 Sensitivity test for both algorithms

System	Simulation outcomes	Parameters to be tested	T value	df	P value
The current landing system	Reactive actions	Deceleration 50%	– - 1.002	408	0.317
		Deceleration 50%	+ 0.583	388	0.560
		Descent – 50%	-0.704	394	0.482
		Descent + 50%	-0.347	375	0.729
	The additional track miles travelled	Deceleration 50%	– -0.51	408	0.959
		Deceleration 50%	+ 1.335	388	0.183
		Descent – 50%	-0.3	394	0.976
		Descent + 50%	0.371	375	0.711
	The time needed for being transferred	Deceleration 50%	– 1.305	408	0.193
		Deceleration 50%	+ 2.5252	388	0.012
		Descent – 50%	-1.684	394	0.093
		Descent + 50%	-0.375	375	0.708
The current landing system	Reactive actions	Deceleration 50%	– 0.324	400	0.746
		Deceleration 50%	+ 1.811	376	0.071
		Descent – 50%	-0.6	397	0.549
		Descent + 50%	-0.58	389	0.954
	The additional track miles travelled	Deceleration 50%	– 0.960	400	0.388
		Deceleration 50%	+ 1.913	376	0.056
		Descent – 50%	1.358	397	0.175
		Descent + 50%	-0.921	389	0.358
	The time needed for being	Deceleration 50%	– -0.848	400	0.397
		Deceleration	+ -0.05	376	0.960

transferred	50%			
	Descent – 50%	-1.004	397	0.316
	Descent + 50%	-1.663	389	0.097

6.5 Results and Discussion

The results of independent t test are shown in **Table 6-6**, which support both **H1** and **H2** assumed. Firstly, for system reliability, the overall frequency of reactive interaction in the improved system is significantly less than the current landing system. As for the sub-indexes in this category, except for the frequency of the conflict resolution conducted, all the other items show a statistically significant difference. Secondly, as for system efficiency, the improved system performs better with less additional track miles traveled and the fuels burnt. Moreover, the time needed to be transferred has no significant difference, showing that no significant delays are caused.

Table 6-6. Independent t test for the system indexes

<i>Performance indexes</i>		<i>System types</i>	<i>Mean</i>	<i>SD</i>	<i>t/df</i>	<i>p-value</i>
System reliability	The overall frequency	Improved	2.17	0.87	22.50 / 1998	0.01**
		Current	3.25	1.31		
	Conflict resolution	Improved	0.59	0.71	1.66 / 1998	0.10
		Current	0.55	0.57		
	Late descent	Improved	0.72	0.45	10.75 / 1998	0.01**
		Current	1.00	0.69		
	Hovering around at outer area	Improved	0.34	0.47	20.36 / 1998	0.01**
		Current	1.13	1.11		
	Go-around	Improved	0.49	0.50	5.62 / 1998	0.01**
		Current	0.61	0.49		

System efficiency	The additional track miles travelled	Improved	4.75	6.17	4.77 / 0.01**
		Current	5.96	5.44	1998
	The fuels burnt during approach	Improved	25183.14	11731.40	4.63 / 0.01**
		Current	27518.23	11438.65	1998
	The time needed for being transferred	Improved	38169.38	32616.27	1.71 / 0.088
		Current	35830.44	30288.50	1998

*Confidence level is 95%, the p-value less than 0.05 represents a significant difference.

* for p-value = 0.01** means the actual value is less than 0.0001

The simulation results provide insightful findings. First of all, the system's reliability is significantly improved with less frequency of reactive interaction. Less occurrence of late descent, hovering around, and go-around characterizes a landing system with less congestion. For the current landing system, the actions without considering team members' expectations can be a source of errors. Although most of the defective proactive operations are conducted from the outer area (section A), due to limited airspace and time pressure around the terminal area (section C), the negative effect of the incompatible working results is amplified. Accordingly, late descent and go-around are applied to prevent imminent risks around FAF. Furthermore, the execution of hovering around is also crucial to create buffers for the system to manage the congestion. On the contrary, for the landing system with better information transparency, less reactive actions occurred depicts a more reliable system performance with less operational disconnects. The proactive actions considering role-specific SMM

enables the execution of high-speed clearance or efficient approach to satisfy a system's coordinability and consistency. Particularly, the significant reduction of the hovering around executed denotes better capabilities to manage the risks or uncertainty under congested scenarios. In specific, the execution of expedite descent and slower approach achieve prompt mitigation of congestion. Thus, only scarce buffers from hovering around are needed. However, the result of the simulation does not show significant improvements in conflict resolution. One of the possible reasons is that the mutual adaption for conflict resolution has yet to be articulated, which requires future research to explore.

Furthermore, better system efficiency is also expected. For the design of the current system, although error-proof protocols prevent adverse events from occurring, it can jeopardize the efficiency of resource utilization. For example, under congested scenarios or landing instability, ATCOs have to issue extra vectoring to solve the possible collision in the air or landing instability, which increases the track miles traveled and the fuels burnt. What is more, the sudden changes of one aircraft will significantly affect all the surrounding aircraft, causing a chain reaction for requesting more reactive actions. On the contrary, the improved system achieves statistically fewer additional track miles traveled and the fuels burnt without causing a significant delay (the time needed to be transferred to tower controllers). Noticeably, the results also

reflect a better utilization of the current airspace. Fewer hovering around conducted reflects less aircraft are asked to hold still to create buffers under congested scenarios, which contributes to a more seamless air traffic flow.

Other than the direct improvements regarding a system's reliability and efficiency, some indirect benefits from better information transparency can also be considered. Firstly, fewer demands of the reactive operations reliefs ATCOs workload under the contingent scenarios. For the current system, the one-to-one radio channel requires extra workload to disseminate information thoroughly. The excessive mental workload caused harms ATCOs' SA [5, 55]. Consequently, a vicious loop forms, which not only increases the resource consumed but also impacts operators' quality of decision-making. Reversely, the improved information transparency helps ATCOs to be free from conducting frequent and repetitive interaction and hence prevents excessive mental workload. Nevertheless, future research is still pending. In this work, the critical information used in level 1 SA serves as a leverage point to facilitate information transparency, enabling immediate proactive actions during both implicit and explicit interaction. However, in the process of level 1 SA, what really matters is the combination of cues perceived. Therefore, the identification of the exact cues and pattern in level 1 SA, and how different parties access the combination of cues with their SMM are the questions needed to be solved. Furthermore, the revision of the

training material is also necessary. Novices' SA, mental model, or SMM should be further trained to process extra information collected in the near future.

6.6 Summary

In this chapter, the benefits of information transparency are approached from the perspective of team cognition. The results show significant improvements regarding a system's reliability and efficiency. The corresponding theoretical, practical contribution and potential limitations are concluded as follows.

Theoretical contribution: This work develops a more sophisticated mechanism to study the importance of information transparency. In particular, this research studies the items of information to be shared and the mechanism of the proposed system. In a distributed system without centralized management, landing system, in this case, the sharing of the dynamic goal-changes is promising to facilitate implicit interaction, minimal operational disconnects during an interaction. Furthermore, less operational disconnects also reduce the demands of conducting reactive actions for mitigating possible system risk, which facilitates a more reliable and efficient system. In the future, further issues regarding information transparency should also be investigated for implementing the data-link system in a landing system. For example, types of information should be shared for optimizing error reduction or resource utilization.

Practical contribution: This work can be deemed to the pilot study for the

implementation of data-link. With the inclusion of role-specific SMM, the examination of the rotation between proactive and reactive actions obtains insightful results. Also, it helps to study a system's performance under contingencies, unexpected weather or technical failures are some of the example [8]. Furthermore, the findings of this work also benefit the implementation of Free Flight, facilitating more flexible and free operations between parties. Lastly, the results provide insights for further modification of training materials for both pilots or ATCOs, which helps novices to be aware of SMM consistency.

Despite these contributions, some limitations and future works should be considered. Firstly, in the improved system, the operations modeled are not formally regulated. Thus, the individual difference is a concern. Furthermore, more accurate parameters like the aircraft's deceleration rate, weight or fuels consumption rate are needed for a more realistic simulation.

7 . Conclusion and future work

This chapter concludes the work accomplished in this thesis by presenting three chapters: conclusion, scientific contributions, and limitations.

7.1 Conclusion

To study the occurrence of an adverse event in a complex system, the quality of team coordination and team cognition formed has received extensive attention. However, in the case of a heterogeneous system, traditional shared mental model (SMM) examination is limited and cannot pinpoint the potential SMM breakdown in a systematical manner. In addition, to cover the complexity of the cognitive process in an accident, qualitative approaches are widely adopted to achieve a descriptive understanding, which does not examine an accident's evolving context. Therefore, to close these gaps, a new perspective, called the framework of evolving team cognition (FETC), is proposed. It consists of the concept of role-specific SMMs and agent-based simulation to study how the potential mental model disconnects (MMDs) in both implicit and explicit interactions jointly contribute to defective team cognition. In addition, based on the work accomplished, a pilot study is conducted to examine how team interaction can be improved, positively affecting a system's reliability and efficiency. The corresponding conclusion of Chapters 4, 5, and 6 is provided as follows.

7.1.1. Accident exploration and MMD mapping

First, for MMD mapping, an unstable approach is studied from the perspective of role-specific SMMs. The task-related SMM facilitates the implicit integration of respective working results, and the team-related SMM helps achieve coordination of non-routine interactions to prevent errors. The combination of underlying MMDs characterizes the context of unwanted system performance. Accordingly, the MMDs identified in task-related SMMs can be the onset of system errors. Operations such as improper instructions from ATCOs and efficient approach from pilots are frequently observed. By contrast, the MMDs in team-related SMMs result in a team missing the window for preventing errors. Pilots' overconfidence and late corrective interventions are the major causes for the continuation of an unstable approach. However, conflicting disconnects can be found in contingent scenarios such as unexpected weather or runway changes. They result in a team being unable to form proper and consistent common goals, thereby rendering the team prone to errors.

In this thesis, the concept of the proposed role-specific SMMs is vital to study possible SMM breakdown in a heterogeneous system. Unlike the current SMM research that emphasizes the similarity of SMMs, the role-specific SMM introduces the compatibility between parties, providing a more comprehensive understanding of the negative effects of possible SMM breakdowns. For the SMM similarity, whether

different parties can develop consistent and proper common goals for the current scenario is determined. Furthermore, the potential difficulties in the original version of SMMs can be uncovered by conflicting disconnects. In this case, it is frequently identified when a team is under a contingent scenario, such as unexpected weather. For the compatibility between the SMMs of parties, studying possible operational disconnects can be a leverage point. It enables the operator to pinpoint the hotspots that should be considered during the interaction. Furthermore, by clarifying the underlying informational and evaluative disconnects, insights into further improvements can be obtained [41, 71].

However, some weaknesses regarding the implementation of role-specific SMMs can also be identified. First, content analysis is adopted to identify meaningful themes to determine MMDs; this may lead to the omission of minor MMDs. Specifically, although the major MMDs are identified in Chapter 4, some minor MMDs that are less frequently mentioned by participants can be found. For example, pilots may request short and simple content from ATCOs during an explicit interaction. Second, for the role-specific SMM, operator's expectations are fundamental. However, faulty expectations can be a potential threat to the quality of the results obtained. In fact, this is similar to the concept of SMM accuracy [86, 89]. Accordingly, to avoid these issues properly, participants with high experience are preferred. Furthermore, the examination

of role-specific SMMs still requires additional quantitative procedures to bridge the needs for MMD mapping.

7.1.2. Implementing FETC in an unstable approach

For the implementation of FETC, the results of MMD mapping serve as a fundamental for ABM development. It simulates how an autonomous team adapts to changing conditions. Specifically, in the outer area, the elimination of task-related SMMs is crucial for avoiding the onset of system errors, thus relieving the workload. As for the landing process around the terminal area, the MMDs under team-related SMMs make risk detection ineffective, causing a team to miss the window for preventing urgent risks. Based on the results of exploratory factor analysis (EFA), the MMDs that occur around the terminal area explain over 40% of the variance. Passive information dissemination and the late initiation of corrective interaction result in a team missing the window for preventing the evolution of system errors. It also highlights the necessity of improving a team's capabilities for more sensitive risk detection and mitigation. Combining these issues, possible concerns regarding a team's reactive actions for preventing the occurrence of an adverse event are presented.

In this thesis, the proposed FETC is fundamental to accomplish the research aims. FETC provides a sophisticated mechanism to elucidate the relationship between MMDs, interaction patterns, and team cognition. Specifically, FETC clarifies how the

underlying MMDs in both implicit and explicit interactions jointly cause unwanted system performance in a longitudinal manner. By doing this, the critical operational disconnects can be accordingly pinpointed, identifying the hotspots to be emphasized. However, two possible issues regarding FETC needs to be investigated to overcome potential weakness. In general, the quality of the developed agent-based model is still subject to the examination results of role-specific-SMMs and corresponding MMD mapping. As Chapter 3.4.1 discussed, the validation of MMDs is required. Furthermore, to achieve a more realistic simulation result, the method to obtain the data in a real-life scenario is also critical. Specifically, the measurement of system performance and the corresponding cognitive state should be properly considered.

7.1.3. Toward better information transparency in a landing system

The pilot study for future improvements aims to provide insights for the landing system. As presented in Chapter 4, some informational disconnects, such as the details and overview of the current air traffic flow, can generate multiple MMDs under both task- and team-related SMMs. Then, from the analysis results obtained in Chapter 5, a strong relationship between MMDs and information transparency is identified. Therefore, Chapter 6 develops a more sophisticated mechanism to study how a system can be benefited from eliminating information gaps, which is fundamental to satisfy the needs of role-specific SMMs.

In particular, this research studies the items of information to be shared and how a system reliability and efficiency are improved. By sharing critical information regarding goal changes, both implicit and explicit interactions can be properly conducted without causing requirement contradiction between parties. Therefore, less operational disconnects result in lower demands of conducting reactive actions for mitigating possible system risk. Furthermore, one can also further utilize the current resources without affecting team members. However, to achieve a more practical improvement in information transparency, some future works such as identification of the exact items of information to be shared, the cognitive process for accessing the information shared with the respective SMM, or even the development of a new interface to prevent noise information require further exploration [14, 70].

7.2 Scientific contributions

Based on all the research work accomplished in this thesis, the major contributions are presented in this section. The deliverables are divided into four parts: research fundamental, MMD mapping, FETC implementation, and the pilot study for future improvements.

(1) Research fundamental:

- Role-specific SMMs is proposed by introducing the idea of compatibility to explain the SMM contributions in a heterogeneous system.

- Conflicting disconnects in a team's role-specific SMMs are identified to explain the importance of SMM similarity emphasized by the existing research.
- The relationship between interaction patterns (implicit and explicit interactions) and SMMs (task- and team-related) is determined.
- FETC provides insights for examining the evolving characteristics of team cognition.
- The gaps between a team's cognitive process and the implementation of computer simulation are bridged.

(2) MMD mapping:

- The involvement of MMDs in both implicit and explicit interactions is identified. Specifically, MMDs in task-related SMMs cause incompatible working results. While MMDs in team-related SMMs cause unsatisfactory purposeful coordination for preventing errors.
- The combination of implicit and explicit interactions characterizes the loop for a team to adapt to changing conditions.

(3) FETC implementation:

- The contribution of various MMDs in different landing stages is determined, facilitating the identification of future interventions.

- Implicit interaction is introduced to explain the onset of system errors.
- The importance of information transparency during explicit interaction is highlighted for more effective error prevention.

(4) A pilot study for future improvements:

- The practical benefits (a system's reliability and efficiency) of information transparency from the perspective of elimination of MMDs are approached.
- Sharing information about dynamic goal changes can be a leverage point to satisfy role-specific SMMs.

7.3 Limitations and future work

This section discusses the potential limitations found during research implementation and provides corresponding future work for better result generalization.

(1) Validation of identified MMDs and MMD mapping: In this thesis, the role-specific SMM is a critical fundamental for all entire work accomplished. A team's MMDs can be extracted by determining team members' expectations. However, unlike the traditional methodologies of SMM measurement, a quantitative validation is lacking. It may be difficult to identify the potential MMDs omitted by participants in the interview. Therefore, validation procedures are expected to ensure the accuracy and comprehensiveness of the results.

(2) FETC and system structure: FETC is a structure that emphasizes on the

relationship among MMDs, interaction patterns, and team cognition. In general, the interaction pattern can be treated as a bridge between MMDs and team cognition. However, the rotation between implicit and explicit interactions is subject to the structure of the system. Moreover, in a goal-oriented system with different structures, the contributions of different categories of SMMs may vary. Therefore, this issue deserves more attention to generalize the performance of FETC.

(3) *FETC and the rotation between proactive and reactive actions:* In this thesis, FETC utilizes implicit and explicit interactions to explain team behavior. However, based on what is described in Chapter 6, both interactions can also be conducted in both proactive and reactive purposes, which lead to a more in-depth examination of team interaction. Therefore, in the future, FETC can also be accordingly modified.

(4) *FETC in a real-life scenario:* In this thesis, the implementation of FETC achieves promising results. While the complexity of team cognition is simplified by modeling the connection among operational disconnects in a discrete manner. In the future, different programming techniques can be considered to introduce the interactive process of possible informational and evaluative disconnects for a more realistic and dynamic simulation.

(5) *Improvements in information transparency in the future:* In Chapter 6, the sharing of dynamic goal changes is modeled. With the inclusion of role-specific SMMs,

the selection of the items to be shared can be investigated more comprehensively. Thus, future direction regarding the improvements of information transparency can be identified. Specifically, the items of information should be included in the data-link should be carefully examined. In general, how information sharing facilitates the development of common goals and the provision of acceptable solutions are two aspects that can be considered.

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Appendices–

Appendix 1: Real cases of mental model disconnects

This appendix shows all the cases of the MMDs identified in Chapter 4.

Pilots' MMDs from ATCOs' perspectives			
SMM category	MMD category	Item	Real cases from interview
Task	Informational	Limited information regarding the current air traffic flow	<i>Tower controller #4: Because pilots do not know well about surroundings... So weather information can be provided so pilots know what to expect and how to configure their speed. So that they can slow down when there is a tailwind. And we can give them information on arrival in front of the aircraft and inform them to expedite.</i>
	Evaluative	Prioritize other considerations over the air traffic flow.	<i>Tower controller #2: But some other pilots put in more consideration for passengers' comfort so they prefer to fly slower for a more stable approach. So the pilots' objectives differ</i>
	Operational	The instructions given may not be strictly followed.	<i>Approach controller #1: In order to save fuel, they make a slow descend from high to low altitude. This impedes the descend of other planes behind. For example, when we ask pilots to descend from 10000 to 4000ft where there will be a long stretch</i>

			<i>at 4000ft when they burn fuel</i>
			<i>Approach controller #7: So if the first aircraft descends slowly, the rest will descend very slowly. That's why once they reach the holding stack, they are very high.</i>
Insufficient preparations for nonroutine instructions during peak hours			<i>Tower controller #6: Sometimes pilots take ATCOs in Singapore for granted compared to other countries' ATCOs like in London. They reflect very differently to our instructions. They are supposed to be ready when they reach their holding point, but sometimes they tell us they are not ready.</i>
ATCO instructions may not be timely achieved.			<i>Tower controller #5: Sometimes, its either pilots are not alert or the flight crew have been in discussion and wasted time during that exchange such that they become too high for landing.</i>
Team	Operational	Requesting last minute changes	<i>Approach controller #1: Even if they are too high, they will think that they can make it and try to force it and therefore won't inform the ATCO</i>
ATCOs' MMDs from Pilots' perspectives			
SMM category	MMD category	Item	Real cases from interview

Task	Informational	Insufficient information regarding each of the aircrafts	<p><i>Captain #7:</i></p> <p><i>The ATCO needs to know the aircraft's performance as well. It is not that simple. The speed up and slowdown are at different rates. There is an issue of wake turbulence as well, therefore, you cannot put the aircraft too close. You have to fit the combination properly as well</i></p>
	Operational	The instructions may cause pilots to be unable to stabilize.	<p><i>First Officer #6:</i></p> <p><i>We kept the high speed and maintained up till 5000ft.... We requested to slow down and they (ATCOs) once again requested us to be at high speed as long as we can. We then told them we had to slow down now if not we will not be stabilized.</i></p>
Team	Operational	The late provision of instructions causes pilots difficulty in performing operations appropriately.	<p><i>Captain #8:</i></p> <p><i>It was quite late before the ATCO gave us a heading to turn into intercept the localizer. The ATCO then apologized for giving it too late. The ATCO gave a heading to turn out before intercepting the localizer. It was lucky that there was no aircraft on the other side and this would affect the lateral separation.</i></p>
		Insufficient provision of contextual information for pilots	<p><i>First officer #9:</i></p> <p><i>Personally, I feel thankful for the information and I would keep that in mind. What is my current state of the aircraft and the traffic ahead of me is what I want to know.</i></p>

		Insufficient provision of details of the instructions given	<p><i>Captain #7:</i></p> <p><i>During the communication, as long as ATCOs provide the remaining track miles and assigned airspeed, then I will be able to enact a plan accordingly.</i></p>
Conflicting disconnects			
SMM category	MMD category	Item	Real cases from interview
		Fuel preservation	<p><i>Approach controller #1:</i></p> <p><i>Pilots want to save fuel to avoid getting into trouble with management when they compare between pilots in the community, Pilots start to ease off when they descend. In order to save fuel, they make a slow descend from high to low altitude. This impedes the descend of other planes behind.</i></p>
Task	Evaluative		<p><i>First officer #3:</i></p> <p><i>The ATCO said I had about 40nm track miles. As it was still a long way to go I took my time to descend, there is no point descending myself to the deck height and drag myself in. This would have wasted a lot of fuel.</i></p>
		Weather avoidance	<p><i>Tower controller #3:</i></p> <p><i>If there is a cloud in the middle of the path, will you try to ask them to avoid this cloud?...</i></p> <p><i>If they really have to, they will have to go through. But best as they can, they will try to avoid. Unless it is very close to finals, they have to come in through the clouds.</i></p>

Captain #7:

If there is a storm ... Sometimes we might ask for shortcuts for avoiding weather. We would have to ask for it ourselves. I would not want to wait till the ATCOs give the instruction. The radar might not pick it up as clearly by the ATCOs. The ATCO might not be able to see it the way the pilot do. There are different thresholds of different pilots to avoid the weather.

Appendix 2: Questionnaire for Chapter 5

This appendix presents the survey used for conducting Exploratory Factor Analysis (EFA) for validating the simulation developed in Chapter 5. The survey for pilots and ATCOs were respectively spread and designed.

Study the context of unstable approach by introducing agent-based model and interaction conflicts

Dear participants:

This research aims to investigate how an unstable approach occurred during a landing. In this work, the interaction process between pilots and ATCOs during the landing phase serves as the research foundations. Based on the previous work done, several operations highly connected to the interaction breakdown during the landing phase have been identified. This questionnaire aims to investigate how frequent the risky operations occur under the scenario of unstable approach. The data collected will be used to develop an agent-based model to simulate an aircraft's landing stability.

This survey is consists of two parts, including: 1. Participants' profile, 2. Evaluating the frequency of interaction breakdown occurred under the scenario of unstable approach. 3. Rating the relational strength between unstable approach and the interaction breakdown identified.

For pilots:

Section 1: Participants profile

1. Position: ☐Second officer / ☐First officer / ☐Captain
2. Gender: ☐Male / ☐Female
3. Age:
4. Working experience (flying hour):

Section 2: Evaluating the frequency of interaction breakdown occurred under the scenario of unstable approach

In this section, please rate how frequent the operations listed are executed under the scenarios of unstable approach based on your subjective experience. Five operations related to interaction conflicts are included. In addition, two factors are involved to study how a team adapts to the environment changes, the factors are 1. remaining track miles (100nm / 50nm / 30nm / 15nm), and 2. the appropriateness of landing profile (stable state based on the STAR requirements / unstable state with excessive airspeed or altitude).

With the combination of the two factors involved, a total of 8 scenarios are included, which is shown in the figure below. For example, cell 1 refers to the scenario of which the aircraft crossed the STAR of 100nm with stable state.

In accordance these eight scenarios, please rate the frequency of the following operations conducted in the case of unstable approach.

1. *To fully utilize the current airspace, ATCOs provide non-routine instructions to expedite the landing process:* Due to peak hour, unexpected weather, or contingencies, ATCOs try to expedite the landing state and fully utilize the airspace by providing non-routine instructions, relevant instructions include high-speed clearance, taking a short-cut, or late descent. However, due to the reduction of the time and the track miles available, it increases the uncertainty of achieving a safe landing.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

2. *Insufficient considerations of aircraft's capabilities difference when providing non-routine instructions:* Due to the unequal information sharing, it is challenging

for ATCOs to consider aircraft's payload and capabilities difference when providing non-routine instructions during peak hour or contingencies.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

3. *ATCOs do not provide sufficient reminders for pilots to notice their current landing state where needed:* When a aircraft's landing stability is subject to factors like separation, unexpected weather, or the aircraft's own landing state, ATCOs do not actively remind pilots for improving their awareness.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

4. *ATCOs do not provide sufficient information when the non-routine instructions are given:* When ATCOs are providing non-routine instructions due to congestion, unexpected weather, or contingencies, they do not provide sufficient intention expression, surroundings information or relevant details for pilots to understand ATCOs' requirements.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

5. *Insufficient reminders from ATCOs to remind pilots taking care of the landing state when the landing stability is questionable:* ATCOs do not provide reminders for pilots to actively adjust the landing stability.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

6. *The late detection and intervention from ATCOs for the unstable landing state:* ATCOs do not detect and intervene the unstable landing state with extra

instructions as early as possible, which makes pilots miss the window for stabilize the aircraft

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

Section 3: Identifying how interaction conflicts contribute to unstable landing state.

This section aims to examine how the conflicts during the team interaction contribute to the occurrence of unstable approach. Please rate how strong the connection between the interaction conflicts and unstable approach is. Based on the previous work done, 10 items are included.

- When ATCOs are providing non-routine instructions, like high-speed clearance, late descent, or taking a short cut to fully utilize the current airspace. The reduction of time and track miles available increase the uncertainty for pilots to land the aircraft safely.
☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
- Due to the goal and subjective priorities difference, pilots may not execute the instructions strictly and timely.
☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
- Due to the unequal information sharing, it makes ATCOs hard to consider aircraft's payload or capabilities difference while providing non-routine instructions to utilize the airspace.
☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
- When pilots are receiving questionable non-routine instructions, they do not respond their concerns immediately.
☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
- When ATCOs are providing non-routine instructions due to the contingent needs, they do not provide the surroundings information for pilots to understand the current state.
☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
- Pilots insist on mitigating unstable landing state on spot when the stability is questionable, instead of asking extra instructions from ATCOs to stabilize the aircraft.

- ☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
7. When ATCOs are providing non-routine instructions due to the contingent needs, ATCOs do not provide sufficient intention expression or operational details for pilots to understand the requirements.
- ☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
8. Insufficient reminders from ATCOs to remind pilots taking care of the landing state when the landing stability is questionable.
- ☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
9. Pilots' late requests for extra vectoring or instructions (eg, extra track miles) for stabilizing the aircraft when the landing stability is questionable.
- ☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)
10. ATCOs' late detection and intervention when the landing stability is questionable.
- ☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

-End-

For ATCOs:

Section 1: Participants profile

1. Position: ☐ Tower controller / ☐ Approach controller
2. Gender: ☐ Male / ☐ Female
3. Age:
4. Working experience (years):

Section 2: Evaluating the frequency of interaction breakdown occurred under the scenario of unstable approach

In this section, please rate how frequent the operations listed are executed under the scenarios of unstable approach based on your subjective experience. Five operations related to interaction conflicts are included. In addition, two factors are involved to study how a team adapts to the environment changes, the factors are 1. remaining track miles (100nm / 50nm / 30nm / 15nm), and 2. the appropriateness of landing profile (stable state based on the STAR requirements / unstable state with excessive airspeed or altitude).

With the combination of the two factors involved, a total of 8 scenarios are included, which is shown in the figure below. For example, cell 1 refers to the scenario of which the aircraft crossed the STAR of 100nm with stable state.

In accordance these eight scenarios, please rate the frequency of the following operations conducted in the case of unstable approach.

1. *Pilots' unresponsiveness to the reception of inappropriate instructions:* Due to the unequal information sharing, it is challenging for ATCOs to consider aircraft's payload and capabilities difference when providing non-routine instructions during peak hour or contingencies. While, some pilots may not respond the instructions given immediately to modify the content of instructions.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

2. *Pilots' inaccurate execution or late accomplishment of the instructions given:* Due to inconsistent priorities between pilots and ATCOs, some pilots do not strictly follow or accomplish the instructions at the required time gate.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

3. *Under the scenarios prone to landing instability, pilots insist on conducting energy management immediately:* When a aircraft's landing stability is questionable, pilots insist on addressing the landing risks immediately, for example, increasing

the drag to offset excessive kinetic energy or potential energy, rather than asking for extra instructions from ATCOs to stabilize the landing state.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

4. *Pilots' requests for the last minute changes to stabilize the landing state:* When a aircraft's landing stability is questionable, pilots miss the proper window for asking extra instructions to stabilize the aircraft, making ATCOs hard to provide immediate instructions for pilots to stabilize the aircraft.

	100nm ~ 50nm	50nm ~ 30nm	30m ~ 15nm	15nm ~ 10nm
Stable state				
Unstable state				

*Please rate the frequency with the percentage (%)

**Minimum percentage is 5% / Maximum percentage is 100%

Section 3: Identifying how interaction conflicts contribute to unstable landing state.

This section aims to examine how the conflicts during the team interaction contribute to the occurrence of unstable approach. Please rate how strong the connection between the interaction conflicts and unstable approach is. Based on the previous work done, 10 items are included.

1. When ATCOs are providing non-routine instructions, like high-speed clearance, late descent, or taking a short cut to fully utilize the current airspace. The reduction of time and track miles available increase the uncertainty for pilots to land the aircraft safely.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

2. Due to the goal and subjective priorities difference, pilots may not execute the instructions strictly and timely.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

3. Due to the unequal information sharing, it makes ATCOs hard to consider aircraft's payload or capabilities difference while providing non-routine instructions to utilize the airspace.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

4. When pilots are receiving questionable non-routine instructions, they do not respond their concerns immediately.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

5. When ATCOs are providing non-routine instructions due to the contingent needs, they do not provide the surroundings information for pilots to understand the current state.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

6. Pilots insist on mitigating unstable landing state on spot when the stability is questionable, instead of asking extra instructions from ATCOs to stabilize the aircraft.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

7. When ATCOs are providing non-routine instructions due to the contingent needs, ATCOs do not provide sufficient intention expression or operational details for pilots to understand the requirements.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

8. Insufficient reminders from ATCOs to remind pilots taking care of the landing state when the landing stability is questionable.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

9. Pilots' late requests for extra vectoring or instructions (eg, extra track miles) for stabilizing the aircraft when the landing stability is questionable.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

10. ATCOs' late detection and intervention when the landing stability is questionable.

☐ 1 (no relation) / ☐ 2 / ☐ 3 / ☐ 4 / ☐ 5 / ☐ 6 / ☐ 7 (Extremely strong relation)

-End-

Appendix 3: Raw data for statistics in Chapter 5

This appendix presents the raw data collected for statistical procedures. The simulation results were divided into three scenarios, including the landing between 100 and 50 Nm, the landing between 30 and 15 Nm and the whole landing process. The number denotes the frequency of the operation conducted in a round of simulation. Furthermore, the last table presents the survey results used for EFA.

Simulation results: Landing between 100 and 50 Nm									
Op_1	Op_2	Op_3	Op_4	Op_5	Op_6	Op_7	Op_8	Op_9	Op_10
1	0	2	0	2	0	1	2	0	1
1	0	1	0	0	1	1	0	1	1
1	0	0	0	1	0	0	1	1	1
1	0	0	0	1	1	0	1	0	1
0	0	0	0	0	0	0	0	0	0
2	0	0	0	2	1	1	0	2	1
0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	1	1	1	0
1	0	0	0	0	0	0	0	1	1
0	0	1	1	0	1	0	1	0	1
0	1	0	2	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0
1	0	0	0	1	1	1	0	1	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	1	0	0	1	1	0	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	1	1	0

0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0	1	0
0	0	1	0	0	0	0	0	0	1
1	0	0	0	1	1	0	0	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	1	1	1
1	0	2	1	2	0	0	1	1	1
1	0	0	0	1	0	1	0	0	1
0	0	0	1	0	0	0	0	0	0
1	0	0	1	0	1	0	0	0	0
0	0	1	1	1	0	0	1	0	1
0	0	0	0	0	0	0	0	0	0
0	0	1	0	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	1	0	1
1	0	0	1	1	0	0	1	1	1
0	0	1	0	0	0	0	0	0	0
1	0	1	0	1	0	1	1	2	1
0	0	2	0	0	0	2	0	2	2
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0	1	1
0	0	1	1	0	0	0	1	1	0
0	0	1	1	0	0	0	0	1	1
1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	1	0	1	1	0
0	0	0	0	0	0	0	0	0	0
1	0	1	0	2	1	2	1	0	2
0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	2	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

1	0	0	0	0	0	1	1	1	1
0	0	1	0	1	0	1	0	1	0
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0
0	0	1	1	1	0	0	1	0	1
1	0	1	1	0	1	1	1	1	0
0	0	1	0	0	1	0	1	0	1
0	0	0	1	0	0	0	0	0	0
1	0	1	0	1	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0
0	1	0	1	0	0	0	1	1	0
0	0	0	0	0	0	0	0	0	0
1	0	0	2	0	1	1	1	1	0
0	0	0	0	0	0	0	0	0	0
0	0	1	1	1	0	1	0	0	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	0	0	1	1	1	0	1	0
2	0	1	0	1	1	1	0	2	1
0	0	0	0	0	0	0	0	0	0
1	0	1	0	0	2	0	1	1	2
0	1	1	1	1	1	0	1	1	1
0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	1	1	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	0	1	1
0	0	1	0	1	1	0	0	1	1
1	0	0	0	0	1	0	0	1	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	1	0	1	0	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	1	0	0	0	1	0	1
0	0	1	1	0	1	0	1	1	0
0	0	1	0	1	0	0	0	1	1

0	0	0	1	0	0	0	0	0	0
0	1	1	1	0	1	0	1	0	1
0	0	0	0	0	0	0	0	0	0
0	0	1	1	0	0	0	1	1	0
0	0	1	0	0	1	0	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	1	0	2	1	1	0	1	2
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	1	1	0	0	1	1	0
0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0
0	0	0	2	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	1	1	0	0	0	1	1
0	0	2	0	1	1	1	1	2	2
0	0	1	1	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0	0
0	0	2	1	0	1	1	0	2	0
1	0	0	1	1	1	1	1	1	1
1	0	0	1	1	0	0	1	1	1
1	0	0	0	0	0	1	0	0	1
0	0	1	0	1	0	0	0	1	1
1	0	1	0	0	1	0	0	1	1
0	0	1	0	0	0	0	1	1	1
0	0	1	0	1	0	0	0	0	1
1	0	0	1	1	0	0	1	1	0

0	0	0	0	0	0	0	0	0	0
0	0	1	1	0	1	1	0	1	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0
0	0	0	2	0	0	0	0	0	0
1	0	0	0	0	1	0	1	1	1
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0
39	4	52	48	37	37	27	41	60	55
19.50%	2.00%	26.00%	24.00%	18.50%	18.50%	13.50%	20.50%	30.00%	27.50%

*The frequency of the operations that occur.

Simulation results: Landing between 30 and 15 Nm									
Op_1	Op_2	Op_3	Op_4	Op_5	Op_6	Op_7	Op_8	Op_9	Op_10
0	1	0	1	0	1	1	1	1	1
1	0	1	1	1	1	2	1	2	2
1	0	0	0	0	1	1	0	1	0
2	0	1	1	2	2	2	2	1	2
1	0	1	1	1	1	1	1	1	1
1	0	0	2	1	1	1	1	1	1
1	0	1	0	2	2	1	1	2	0
0	0	1	0	1	0	1	1	1	1
1	1	0	1	2	2	1	1	1	2
1	0	1	1	1	1	1	1	1	1
1	0	0	0	0	1	1	1	1	1
1	0	0	1	1	0	1	1	1	1
1	0	0	1	1	1	1	1	1	1
0	0	1	1	0	1	1	1	1	1
0	0	1	0	1	1	1	1	1	1
0	1	0	1	1	0	1	1	1	1
2	0	0	1	1	2	1	1	0	0
1	0	2	1	0	2	1	2	1	2
1	0	1	0	1	2	2	1	1	2
1	0	1	0	2	1	2	2	2	2
0	0	1	1	1	0	1	1	1	1
1	0	0	1	1	1	1	1	1	0

1	0	1	1	1	1	2	2	2	2
0	0	1	0	0	1	1	1	1	1
1	0	1	1	1	2	1	2	2	2
0	0	1	1	1	1	1	0	1	1
0	0	2	1	2	1	2	2	1	2
0	1	0	1	1	1	1	1	1	0
1	0	0	1	1	1	1	1	1	1
1	0	0	1	1	1	1	0	0	1
1	0	1	0	2	2	1	2	2	2
1	0	0	0	1	1	1	1	1	0
1	0	1	0	1	1	1	0	1	0
1	0	1	0	1	2	2	1	1	1
1	1	1	1	1	1	1	1	2	2
1	0	1	0	1	1	1	1	1	0
1	0	0	0	1	1	1	1	1	1
0	0	1	0	1	1	1	1	1	1
1	0	0	1	1	1	1	1	1	1
0	0	2	1	2	1	1	2	2	2
0	0	1	0	1	0	1	1	0	0
1	0	0	0	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1
0	0	1	0	1	1	1	1	1	1
1	0	0	0	1	1	1	0	1	0
1	0	0	1	0	1	1	1	0	1
0	0	1	1	1	1	1	0	1	1
1	0	0	1	1	1	1	1	1	1
1	0	0	1	0	1	1	0	1	0
0	0	1	2	1	0	1	1	0	1
1	1	0	1	0	1	1	1	1	0
2	1	0	1	1	1	2	2	2	2
2	0	0	0	2	2	2	1	2	2
0	1	0	1	0	1	1	1	1	1
1	1	1	1	2	1	2	1	1	1
1	0	0	1	1	1	1	1	0	1
2	0	1	0	2	1	2	2	2	1
1	0	0	0	1	0	1	0	1	1

0	0	1	1	1	1	1	1	1	1
2	0	1	1	0	2	1	2	0	1
0	0	1	2	1	0	1	1	1	1
1	0	1	1	2	2	1	1	2	0
1	0	1	1	1	0	1	1	2	2
0	0	1	0	1	1	1	1	1	1
0	0	1	0	1	1	1	1	1	1
0	0	1	2	0	1	1	0	0	0
1	0	0	0	1	1	1	1	1	1
1	1	0	1	1	0	1	1	0	1
0	1	0	1	1	1	1	1	1	1
1	1	0	1	1	1	1	1	0	1
0	1	1	1	2	1	2	2	1	1
0	0	1	0	0	1	1	1	1	1
1	0	0	1	1	0	1	0	1	1
0	1	2	1	2	2	1	2	2	2
1	0	0	0	1	0	1	1	1	1
2	0	1	0	2	2	1	1	2	2
1	0	1	0	0	1	1	1	1	1
1	0	2	1	1	1	1	1	2	1
0	0	1	0	1	0	1	0	1	1
1	0	0	1	1	1	1	0	1	1
1	0	0	0	1	0	1	1	0	1
2	0	1	1	0	1	2	2	2	1
0	0	1	1	1	0	1	1	1	1
1	0	0	1	1	1	1	0	0	1
0	0	2	1	1	0	1	2	1	1
0	1	0	1	1	1	1	0	0	1
1	0	0	0	1	1	1	1	0	1
1	1	2	1	2	2	2	2	2	1
1	0	1	0	2	1	2	2	2	1
0	0	1	1	0	1	1	1	1	1
1	0	1	1	1	0	1	1	1	1
2	0	1	0	2	2	2	1	2	2
0	0	1	1	1	0	1	0	1	0
1	1	1	1	1	1	1	2	1	2
0	0	1	1	1	1	1	1	1	1

0	0	1	0	1	1	1	1	0	1
1	0	1	1	1	1	1	0	1	1
0	1	1	1	1	1	1	0	1	1
1	1	0	1	2	1	2	2	2	1
0	0	1	1	0	1	1	1	1	1
1	1	1	1	2	2	1	2	2	2
1	0	0	0	1	0	1	0	1	1
1	1	0	1	1	1	1	1	1	1
1	0	0	2	1	0	1	0	0	1
1	0	1	1	0	1	1	1	1	1
0	0	1	0	1	0	1	1	0	1
1	1	2	2	1	2	2	1	2	2
0	0	2	0	2	0	1	1	2	2
2	0	0	0	1	2	2	1	2	1
1	0	0	0	0	1	1	1	1	1
0	1	1	1	2	2	1	2	0	2
1	0	0	0	0	1	1	1	1	1
1	1	0	2	1	1	1	1	1	1
2	0	0	2	1	2	2	2	2	2
0	1	0	2	1	1	1	1	1	1
1	1	1	2	2	2	2	2	2	1
0	0	1	0	0	1	1	0	0	1
0	0	1	0	1	1	1	0	1	1
0	2	0	2	2	0	1	1	2	2
0	0	2	1	1	1	2	1	2	1
1	0	0	2	1	0	1	1	1	0
0	0	1	0	0	1	1	0	1	0
1	0	0	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	0	1
0	0	2	1	1	1	2	2	2	0
0	0	1	2	1	1	1	1	1	1
0	1	0	1	1	1	1	1	1	1
0	0	1	0	1	1	1	1	1	1
1	0	0	2	1	1	1	1	1	1
0	0	2	0	1	2	2	2	0	2
0	1	1	1	1	0	1	1	1	0
1	0	0	0	0	1	0	1	0	1

0	0	1	2	1	1	1	1	1	1
2	0	0	1	1	1	2	2	1	2
1	0	1	1	0	1	1	1	0	1
1	0	0	1	1	1	1	1	1	0
1	0	1	0	1	2	2	1	1	2
0	0	1	0	1	0	1	1	1	1
1	0	0	0	0	1	1	0	0	0
1	0	0	0	1	0	1	1	1	1
1	0	1	0	0	2	1	0	1	0
99	30	95	105	140	139	168	143	149	147
49.50%	15.00%	47.50%	52.50%	70.00%	69.50%	84.00%	71.50%	74.50%	73.50%

*The frequency of the operations that occur.

Simulation results: The whole landing process									
Op_1	Op_2	Op_3	Op_4	Op_5	Op_6	Op_7	Op_8	Op_9	Op_10
1	1	2	1	2	1	2	3	1	2
2	0	2	1	1	2	3	1	3	3
2	0	0	0	1	1	1	1	2	1
3	0	1	1	3	3	2	3	1	3
1	0	1	1	1	1	1	1	1	1
3	0	0	2	3	2	2	1	3	2
1	0	1	1	2	2	1	1	2	0
0	0	1	0	1	0	1	1	1	1
2	1	0	1	2	2	2	2	2	2
2	0	1	1	1	1	1	1	2	2
1	0	1	1	0	2	1	2	1	2
1	1	0	3	1	0	1	1	1	1
1	0	0	2	1	1	1	1	1	1
1	0	1	1	1	2	2	1	2	1
0	0	1	0	1	1	1	1	1	1
0	1	0	1	1	0	1	1	1	1
2	0	0	1	1	2	1	1	0	0
1	0	2	1	0	2	1	2	1	2
2	0	2	0	1	3	3	1	2	3
1	0	1	0	2	1	2	2	2	2
0	0	1	1	1	0	1	1	1	1
1	0	1	1	1	1	1	2	2	0

1	0	1	1	1	1	2	2	2	2
1	0	1	0	0	2	1	1	2	1
1	0	2	1	1	2	1	2	2	3
1	0	1	1	2	2	1	0	2	2
0	0	2	1	2	1	2	2	1	2
0	1	0	1	1	1	1	1	1	0
1	0	1	1	1	2	1	2	2	2
2	0	2	2	3	1	1	1	1	2
2	0	1	0	3	2	2	2	2	3
1	0	0	1	1	1	1	1	1	0
2	0	1	1	1	2	1	0	1	0
1	0	2	1	2	2	2	2	1	2
1	1	1	1	1	1	1	1	2	2
1	0	2	0	2	2	2	2	2	1
1	0	0	0	1	1	1	1	1	1
0	0	1	0	1	1	1	1	1	1
1	0	0	1	1	1	1	1	1	1
0	0	3	1	2	2	1	3	2	3
1	0	1	1	2	0	1	2	1	1
1	0	1	0	1	1	1	1	1	1
1	0	2	1	2	1	2	2	3	2
0	0	3	0	1	1	3	1	3	3
1	0	0	0	1	1	1	0	1	0
1	0	0	1	0	1	1	1	0	1
0	0	2	1	2	1	1	0	2	2
1	0	1	2	1	1	1	2	2	1
1	0	1	2	1	1	1	1	2	2
2	0	0	1	0	1	1	0	1	0
0	0	1	2	1	0	1	1	0	1
2	1	0	2	0	2	1	2	2	0
2	1	0	1	1	1	2	2	2	2
3	0	1	0	4	3	4	2	2	4
0	1	0	2	0	1	1	1	1	1
1	1	1	1	2	1	2	1	1	1
1	0	0	1	1	1	1	1	0	1
2	0	1	2	2	1	2	2	2	1
1	0	0	0	1	0	1	0	1	1

1	0	1	1	1	1	2	2	2	2
2	0	2	1	1	2	2	2	1	1
0	0	1	2	1	0	1	1	1	1
1	0	1	2	2	2	1	1	2	0
1	0	2	2	2	0	1	2	2	3
1	0	2	1	1	2	2	2	2	1
0	0	2	0	1	2	1	2	1	2
0	0	1	3	0	1	1	0	0	0
2	0	1	0	2	1	1	2	2	2
1	1	0	1	1	0	1	1	0	1
0	2	0	2	1	1	1	2	2	1
1	1	0	1	1	1	1	1	0	1
1	1	1	3	2	2	3	3	2	1
0	0	1	0	0	1	1	1	1	1
1	0	1	2	2	0	2	0	1	2
0	1	2	1	2	2	1	2	2	2
1	0	0	0	1	0	1	1	1	1
2	0	1	0	2	2	1	1	2	2
2	0	1	0	1	2	2	1	2	1
3	0	3	1	2	2	2	1	4	2
0	0	1	0	1	0	1	0	1	1
2	0	1	1	1	3	1	1	2	3
1	1	1	1	2	1	1	2	1	2
2	0	1	1	0	1	2	2	2	1
1	0	1	1	1	1	1	2	2	1
1	0	0	1	1	1	1	0	0	1
0	0	3	1	1	1	1	2	2	2
0	1	1	1	2	2	1	0	1	2
2	0	0	0	1	2	1	1	1	1
1	1	2	1	2	2	2	2	2	1
1	0	1	0	2	1	2	2	2	1
0	0	2	2	0	2	1	2	2	2
1	0	1	1	1	0	1	1	1	1
2	0	1	0	2	2	2	1	2	2
0	0	2	2	1	0	1	1	1	1
1	1	2	2	1	2	1	3	2	2
0	0	2	1	2	1	1	1	2	2

0	0	1	1	1	1	1	1	0	1
1	1	2	2	1	2	1	1	1	2
0	1	1	1	1	1	1	0	1	1
1	1	1	2	2	1	2	3	3	1
0	0	2	1	0	2	1	2	2	2
1	1	1	1	2	2	1	2	2	2
1	0	0	0	1	0	1	0	1	1
2	1	1	1	3	2	2	1	2	3
1	0	0	2	1	0	1	0	0	1
1	0	1	1	0	1	1	1	1	1
0	0	2	1	2	0	1	2	1	1
1	1	2	3	1	2	2	1	2	2
0	0	2	0	2	0	1	1	2	2
2	0	0	0	1	2	2	1	2	1
1	0	0	0	0	1	1	1	1	1
1	1	1	1	2	2	1	2	1	2
1	0	0	0	0	1	1	1	1	1
1	1	0	4	1	1	1	1	1	1
2	0	0	2	1	2	2	2	2	2
0	1	0	2	1	1	1	1	1	1
1	1	1	3	2	2	2	2	2	1
0	0	1	0	0	1	1	0	0	1
0	0	2	1	2	1	1	0	2	2
0	2	2	2	3	1	2	2	4	4
0	0	3	2	1	1	2	2	3	2
1	0	0	2	1	0	1	1	1	0
1	0	1	1	0	1	2	0	1	1
1	0	0	1	1	1	1	1	1	0
0	0	3	2	1	2	2	1	2	1
1	0	2	2	2	2	3	3	3	1
1	0	1	3	2	1	1	2	2	2
1	1	0	1	1	1	2	1	1	2
0	0	2	0	2	1	1	1	2	2
2	0	1	2	1	2	1	1	2	2
0	0	3	0	1	2	2	3	1	3
0	1	2	1	2	0	1	1	1	1
2	0	0	1	2	0	1	1	2	1

0	0	1	2	1	1	1	1	1	1
2	0	1	2	1	2	3	2	2	2
1	0	1	1	0	1	1	1	0	1
1	0	0	1	1	1	1	1	1	0
1	0	1	1	1	2	2	1	1	2
0	0	1	2	1	0	1	1	1	1
2	0	0	0	0	2	1	1	1	1
1	0	0	0	1	0	1	1	1	1
1	0	1	1	0	2	1	0	1	0
138	34	147	153	177	176	195	184	209	202
34.50%	8.50%	36.75%	38.25%	44.25%	44.00%	48.75%	46.00%	52.25%	50.50%

*The frequency of the operations that occur.

Survey results (Section 3) for EFA										
	Op_1	Op_2	Op_3	Op_4	Op_5	Op_6	Op_7	Op_8	Op_9	Op_10
#1	3	5	3	6	7	4	3	2	2	1
#2	2	2	4	5	5	2	2	4	4	6
#3	5	7	3	7	6	6	7	6	3	2
#4	3	4	4	3	3	4	3	4	4	4
#5	4	2	5	6	6	3	6	3	3	3
#6	4	3	3	5	6	4	5	5	4	4
#7	5	4	3	5	4	4	5	5	6	4
#8	2	2	2	3	3	1	3	2	2	2
#9	4	2	2	3	5	3	5	3	4	4
#10	6	5	2	2	2	4	2	2	2	2
#11	6	7	7	3	4	6	6	3	4	6
#12	3	5	6	3	5	3	6	2	3	2
#13	3	4	5	6	7	4	5	2	2	2
#14	2	6	6	7	6	2	5	5	3	2
#15	6	6	5	5	5	2	6	3	6	3
#16	5	2	6	6	5	6	6	4	2	2
#17	5	6	4	5	2	5	5	4	4	5
#18	6	6	5	5	4	5	6	3	6	5
#19	2	3	5	4	2	2	4	1	2	3
#20	2	6	6	5	6	5	6	3	7	7
#21	6	6	5	5	4	5	6	3	6	5
#22	3	6	1	2	2	3	3	4	5	2

#23	3	4	2	7	7	7	7	1	6	1
#24	6	2	5	1	4	5	3	1	5	5
#25	4	4	4	5	5	4	4	4	4	4
#26	2	5	5	6	6	5	5	2	4	4
#27	4	4	4	5	5	4	4	4	4	4
#28	6	4	6	6	5	4	6	4	5	5
#29	3	5	5	4	3	3	4	3	4	4
#30	5	4	5	7	7	5	6	4	2	3
#31	5	6	4	5	5	6	5	2	3	2
#32	4	3	2	4	2	4	4	1	3	2
#33	3	3	4	3	2	3	4	4	2	4
#34	6	4	6	6	6	4	6	4	2	4
#35	2	2	6	5	4	6	3	4	5	5
#36	5	3	6	5	2	6	5	5	5	3
#37	4	5	6	6	3	5	5	1	3	5
#38	5	6	2	6	2	3	6	2	5	5
#39	3	2	6	6	5	5	4	4	4	5
#40	6	4	6	7	7	5	7	3	3	3
#41	4	3	4	5	5	3	4	4	5	3
#42	4	3	6	6	5	6	4	4	5	4
#43	6	6	6	5	7	7	6	5	5	5
#44	6	4	5	4	5	4	4	4	3	3
#45	2	4	3	4	2	3	4	3	3	3
#46	5	6	6	6	5	5	7	5	6	6
#47	2	2	3	6	4	2	5	2	2	3
#48	4	4	6	7	5	5	6	4	5	6
#49	5	5	6	6	4	6	5	4	2	3
#50	5	2	6	6	6	4	6	3	3	3
#51	4	2	6	5	6	6	4	4	5	5
#52	4	2	6	6	6	5	6	3	3	4

*Likert 7-point scale: 1: the operation has no relation with unstable approach / 7:
operation has extremely strong relation with unstable approach

Appendix 4: Script for Chapter 6

This appendix presents all the attributes, parameters and codes developed for the simulation.

Items	Variables
Airspace	sectionA, sectionB, sectionC(35-10Nm), sectionC(10Nm-to-finals)
Entry	a, b, g, h, j (shown in Fig. 6-2)
Light aircraft	airspeed, minimum-airspeed, altitude, minimum-altitude, separation-with-preceding-aircraft, the-separation-of-succeeding-aircraft, deceleration-rate-l, descent-rate-l, extra-miles-travelled, fuels-burnt, the-time-for-being-transferred, the-frequency-of-reactive-action, heavy-traffic-mode(on/off; default: off)
Heavy aircraft	airspeed, minimum-airspeed, altitude, minimum-altitude, separation-with-preceding-aircraft, the-separation-of-succeeding-aircraft, deceleration-rate-h (equal to deceleration-rate-l * 0.7), descent-rate-h (equal to descent-rate-l * 0.7), extra-miles-travelled, fuels-burnt, the-time-for-being-transferred, the-frequency-of-reactive-action, heavy-traffic-mode(on/off; default: off)
General function	Description
Record-time	Function Record-time { Set the-time-for-being-transferred = the-frequency-of-the-calculation-conducted }
Calculate-fuels-burnt	Function Calculate-fuels-burnt { Set fuels-burnt = fuels-burnt + air-density* 1 (Light) / 1.5 (Heavy) } 3000~4000 ft: 0.8194 (kg/m3) 4000~5000 ft: 0.7364 (kg/m3) 5000~6000 ft: 0.6601 (kg/m3) 6000~7000 ft: 0.5900 (kg/m3) 7000~8000 ft: 0.5258 (kg/m3) 8000~9000 ft: 0.4671 (kg/m3) 9000~10000 ft: 0.4135 (kg/m3)

	10000~15000 ft: 0.1948 (kg/m3) 15000~20000 ft: 0.0889 (kg/m3)
Calculate-reactive-actions	Function Calculate-reactive-actions { Set the-frequency-of-reactive-action = the-frequency-of-reactive-action +1 }
Transfer-to-tower	Function Transfer-to-tower { Ask aircraft die }
Record-performance	Function Record-performance { Output extra-miles-travelled, fuels-burnt, the-time-for-being-transferred, the-frequent-reactive-action }
Agent function	Description
Conflict-resolution	<i>*When the separation is less than 2 Nm, an aircraft is detoured.</i> Function conflict-resolution { If else separation-with-preceding-aircraft <= 2 Nm [Do detour] [Do decelerate-for-avoiding-conflict] Do Calculate-reactive-actions }
Decelerate-for-avoiding-conflict (light / heavy)	<i>*When the separation is no less than 2 Nm, an aircraft is requested to gradually decelerate. The airspeed of the preceding aircraft is set to be the minimum airspeed. The deceleration rate is determined by the weight of aircraft (light / heavy)</i> Function Decelerate-for-avoiding-conflict { Set minimum-airspeed = airspeed-of-the-preceding-aircraft If else airspeed <= minimum-airspeed [Set airspeed = minimum-airspeed] [Set airspeed = airspeed – deceleration-rate] Advance airspeed Do calculate-fuels-burnt }
Detour (light / heavy)	<i>*When the separation is less than 2 Nm, an aircraft is requested to be vectored out. To simplify the modelling, aircraft will not advance anymore, even though, the process of deceleration still continues. The deceleration rate is determined by the weight of aircraft (light / heavy)</i> Function detour {

	<p>Set airspeed = airspeed – deceleration-rate</p> <p>If else airspeed <= minimum-airspeed</p> <p> [Set airspeed = minimum-airspeed</p> <p> Set altitude = altitude- descent-rate]</p> <p> [Set airspeed = airspeed – deceleration-rate]</p> <p>Advance 0</p> <p>Set extra-miles-travelled = extra-miles-travelled + airspeed</p> <p>Do calculate-fuels-burnt</p> <p>}</p>
<p>Hovering-around (light / heavy)</p>	<p><i>*When the section C is congested. an aircraft is requested to hover around. While, the deceleration and descent process still continue to follow the STARs regulated. The deceleration and decent rate are determined by the weight of aircraft (light / heavy)</i></p> <p>Function Hovering-around {</p> <p> Set airspeed = airspeed – deceleration-rate</p> <p> If else airspeed <= minimum-airspeed</p> <p> [Set airspeed = minimum-airspeed</p> <p> Set altitude = altitude- descent-rate]</p> <p> [Set airspeed = airspeed – deceleration-rate]</p> <p> Advance 0</p> <p> Set extra-miles-travelled = extra-miles-travelled + airspeed</p> <p> Do calculate-fuels-burnt</p> <p> Do Calculate-reactive-actions</p> <p>}</p>
<p>Hover-at-high-altitude (light / heavy)</p>	<p><i>*When the section C is congested. an aircraft is requested to hover around. An aircraft will keep decelerating. While, it can maintain the current altitude to save fuels. The deceleration and decent rate are determined by the weight of aircraft (light / heavy)</i></p> <p>Function Hover-at-high-altitude {</p> <p> Set airspeed = airspeed – deceleration-rate</p> <p> If else airspeed <= minimum-airspeed</p> <p> [Set airspeed = minimum-airspeed]</p> <p> [Set airspeed = airspeed – deceleration-rate]</p> <p> Advance 0</p> <p> Set extra-miles-travelled = extra-miles-travelled + airspeed</p> <p> Do calculate-fuels-burnt</p> <p> Do Calculate-reactive-actions</p> <p>}</p>

Follow-STARs	<p><i>*As shown, regulated airspeed and altitude are shown based on the STARs. An aircraft cannot be slower than the minimum airspeed and lower than the minimum altitude.</i></p> <p>Function Follow-STARs {</p> <p> Check route</p> <p> If route(a-c) or route(b-c)</p> <p> Set minimum-airspeed = 250 kt</p> <p> Set minimum-altitude = 10000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(c-d)</p> <p> Set minimum-airspeed = 220 kt</p> <p> Set minimum-altitude = 10000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(d-e) or route(f-e)</p> <p> Set minimum-airspeed = 200 kt</p> <p> Set minimum-altitude = 7000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(g-f) or route(h-f)</p> <p> Set minimum-airspeed = 220 kt</p> <p> Set minimum-altitude = 7000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(e-i) or route(j-i)</p> <p> Set minimum-airspeed = 170 kt</p> <p> Set minimum-altitude = 3000 ft</p> <p> Do Adjust-flight-state</p> <p> }</p>
Adjust-flight-state (light / heavy)	<p><i>*An aircraft will decelerate and descend to the STAR regulated in the Function of "follow-STARs". In addition, an aircraft will decelerate to minimum airspeed before descending. The deceleration and decent rate are determined by the weight of aircraft (light / heavy)</i></p> <p>Function Adjust-flight-state {</p> <p> Heading next-STAR</p> <p> Set airspeed = airspeed – deceleration-rate</p> <p> If else airspeed <= minimum-airspeed</p> <p> [Set airspeed = minimum-airspeed</p> <p> Set altitude = altitude- descent-rate</p> <p> [If altitude = minimum-altitude</p>

	<p>Set altitude = minimum-altitude]]</p> <p>[Set airspeed = airspeed – deceleration-rate]</p> <p>Advance airspeed</p> <p>Do calculate-fuels-burnt</p> <p>}</p>
Late-descent	<p><i>*As shown, late descent is conducted in section C. The minimum altitude will be 1000 ft higher than the STARs.</i></p> <p>Function late-descent {</p> <p> Check route</p> <p> If route(d-e) or route(f-e)</p> <p> Set minimum-airspeed = 200 kt</p> <p> Set minimum-altitude = 7000 ft + 1000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(e-i) or route(j-i)</p> <p> Set minimum-airspeed = 170 kt</p> <p> Set minimum-altitude = 3000 ft + 1000 ft</p> <p> Do Adjust-flight-state</p> <p> Do Calculate-reactive-actions</p> <p> }</p>
Go-around	<p><i>*The function is similar to the Function of “detour”, an aircraft is asked to go around to stabilize the aircraft. It can only be transferred to tower controller when the landing profile satisfy the STAR i (170 kt / 3000 ft)</i></p> <p>Function Go-around {</p> <p> Set airspeed = airspeed – deceleration-rate</p> <p> If else airspeed <= minimum-airspeed</p> <p> [Set airspeed = minimum-airspeed</p> <p> Set altitude = altitude- descent-rate]</p> <p> [Set airspeed = airspeed – deceleration-rate]</p> <p> Advance 0</p> <p> Set extra-miles-travelled = extra-miles-travelled + airspeed</p> <p> Do calculate-fuels-burnt</p> <p> Do Calculate-reactive-actions</p> <p>}</p>
High-speed-clearance-current	<p><i>*The speed restriction is 10 knots faster than STARs regulated.</i></p> <p>Function High-speed-clearance-current {</p> <p> Check route</p> <p> If route(a-c) or route(b-c)</p>

	<p> Set minimum-airspeed = 250 kt + 20 kt Set minimum-altitude = 10000 ft Do Adjust-flight-state If route(c-d) Set minimum-airspeed = 220 kt + 20 kt Set minimum-altitude = 10000 ft Do Adjust-flight-state If route(g-f) or route(h-f) Set minimum-airspeed = 220 kt + 20 kt Set minimum-altitude = 7000 ft Do Adjust-flight-state } </p>
High-speed-clearance-improved (light / heavy)	<p> <i>*The speed restriction is faster than STARs regulated. While, it is subject to the weight of aircraft. Light aircraft can be 20 kt faster due to better capability of deceleration, while heavy aircraft can only be 10 kt faster.</i> </p> <p> Function High-speed-clearance-current { Check route If route(a-c) or route(b-c) Set minimum-airspeed = 250 kt + 20 kt (Light) / 10 kt (Heavy) Set minimum-altitude = 10000 ft Do Adjust-flight-state If route(c-d) Set minimum-airspeed = 220 kt + 20 kt (Light) / 10 kt (Heavy) Set minimum-altitude = 10000 ft Do Adjust-flight-state If route(g-f) or route(h-f) Set minimum-airspeed = 220 kt + 20 kt (Light) / 10 kt (Heavy) Set minimum-altitude = 7000 ft Do Adjust-flight-state } </p>
Efficient-approach	<p> <i>*The aircraft will fly 10 kt slower and 1000 ft higher to save the fuels burnt.</i> </p> <p> Function Efficient-approach { Check route </p>

	<p>If route(a-c) or route(b-c)</p> <p> Set minimum-airspeed = 250 kt - 10 kt</p> <p> Set minimum-altitude = 10000 ft + 1000 ft</p> <p> Do Adjust-flight-state</p> <p>If route(c-d)</p> <p> Set minimum-airspeed = 220 kt - 10 kt</p> <p> Set minimum-altitude = 10000 ft + 1000 ft</p> <p> Do Adjust-flight-state</p> <p>If route(g-f) or route(h-f)</p> <p> Set minimum-airspeed = 220 kt - 10 kt</p> <p> Set minimum-altitude = 7000 ft + 1000 ft</p> <p> Do Adjust-flight-state</p> <p>}</p>
Slower-approach	<p><i>*The aircraft will fly 10 kt slower to create buffers for ATCOs to solve the congestion around section C.</i></p> <p>Function Efficient-approach {</p> <p> Check route</p> <p> If route(a-c) or route(b-c)</p> <p> Set minimum-airspeed = 250 kt - 10 kt</p> <p> Set minimum-altitude = 10000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(c-d)</p> <p> Set minimum-airspeed = 220 kt - 10 kt</p> <p> Set minimum-altitude = 10000 ft</p> <p> Do Adjust-flight-state</p> <p> If route(g-f) or route(h-f)</p> <p> Set minimum-airspeed = 220 kt - 10 kt</p> <p> Set minimum-altitude = 7000 ft</p> <p> Do Adjust-flight-state</p> <p>}</p>
Expedite-descent	<p><i>*In order to solve the congestion in succeeding air traffic flow, pilots can flexibly deploy the configuration to simultaneously decelerate and descend.</i></p> <p>Function late-descent {</p> <p> Check route</p> <p> If route(d-e) or route(f-e)</p> <p> Set minimum-airspeed = 200 kt</p> <p> Set minimum-altitude = 7000 ft</p>

	<pre> Do [Set airspeed = airspeed – deceleration-rate Set altitude = altitude- descent-rate If airspeed = minimum- airspeed Set airspeed = minimum- airspeed If altitude = minimum-altitude Set altitude = minimum- altitude Advance airspeed Do calculate-fuels-burnt] If route(e-i) or route(j-i) Set minimum-airspeed = 170 kt Set minimum-altitude = 3000 ft Do [Set airspeed = airspeed – deceleration-rate Set altitude = altitude- descent-rate If airspeed = minimum- airspeed Set airspeed = minimum- airspeed If altitude = minimum-altitude Set altitude = minimum- altitude Advance airspeed Do calculate-fuels-burnt] } </pre>
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Appendix 5: Sensitivity test based on model-based output variance decomposition

In order to test the robustness of the ABM developed in a more comprehensive manner, the sensitivity test based on model-based output variance decomposition is a proper approach. By fitting a regression function of the parameters to the simulation outcomes, the variance of the outcomes can be obtained. Accordingly, the sensitivity of a parameter can be examined by checking the proportion of the variance explained by the parameter. To this end, a regression function with a good fit to the simulation outcomes is a prerequisite which should be firstly achieved. In this test, first-degree, second-degree and third-degree polynomial were applied to fit the simulation outcomes.

To conduct the regression analysis, the range of the parameters to be tested was further divided into multiple levels, helping to obtain a clearer picture of the changing outcomes. As Section 6.4.2 mentioned, the range of the parameters was set to be between + 50 % and -50% of the nominal value. In this test, five levels were defined, comprising: 1. Nominal value -50%, 2. Nominal value -25%, 3. Nominal value, 4. Nominal value +25% and 5. Nominal value +50%. Then, ordinary least square regression (OLS) is a common approach to transfer the output into descriptive relationships (See **Equation 1**) [137]. By definition, the simulation runs a number of

rounds over various values of the parameter to be tested. y_i is the outcome of simulation, y_{av} is the average of outcomes, and y_j^r is the predicted outcome from the regression model.

$$R^2 = 1 - \frac{\sum (y_i - y_j^r)^2}{\sum (y_i - y_{av})^2}$$

Equation 1: Ordinary least square

The results of the regression analysis are shown in the table below. In general, no regression function with good fit was identified, showing that the changes of deceleration and descent rate were unable to explain the variance of simulation outcomes. To present the trend of simulation outcomes, the distribution of sample points was also displayed.

The current landing system				
Deceleration rate	Order of nonlinearity	1st	2nd	3rd
	The frequency of reactive actions	0.005	0.005	0.006
	R^2			
Descent rate	The additional track miles travelled	0.002	0.002	0.003
	The time needed to be transferred	<0.001	0.002	0.004
	R^2			
Descent rate	Order of nonlinearity	1st	2nd	3rd
	The frequency of reactive actions	<0.001	<0.001	0.001
	R^2			
	The additional track miles travelled	<0.001	<0.001	<0.001
	The time needed to be transferred	0.001	0.002	0.002
	R^2			
The improved landing system				
Deceleration rate	Order of nonlinearity	1st	2nd	3rd

R^2	The frequency of reactive actions	0.001	0.004	0.008
	The additional track miles travelled	<0.001	0.003	0.006
	The time needed to be transferred	<0.001	<0.001	0.001
Descent rate	Order of nonlinearity	1st	2nd	3rd
R^2	The frequency of reactive actions	<0.001	<0.001	<0.001
	The additional track miles travelled	0.005	0.007	0.007
	The time needed to be transferred	<0.001	<0.001	0.004

The current landing system
Parameter: Deceleration rate

- : Observation
- : 1st
- - - : 2nd
- . - : 3rd

The improved landing system
Parameter: Deceleration rate

- : Observation
- : 1st
- - : 2nd
- . : 3rd

The improved landing system Parameter: Descent rate

- : Observation
- : 1st
- - - : 2nd
- . . : 3rd