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EXECUTIVE SUMMARY

This report corresponds to D2.3 Report about Validation of ATM Architecture of Greener Air Traffic Operations. The work reported is related to WP2.3 Validation of Greener ATM architecture.

WP2.3 is organized in two different tasks:

- Task 2.3.1 Fast-Time Simulation of selected ATM scenarios
- Task 2.3.2 Architecture Validation

Deliverable D2.3 covers the work performed in both Task 2.3.1 and Task 2.3.2.

The information contained in this report provides a comprehensive description of validation methodology, process and results of greener ATM architecture developed in WP2.2. Typical ATM scenarios have been identified and simulated using visualization methods. Dynamic evolution within the ATM architecture through the whole flight process have been demonstrated. The result of the validation will support improvement of the models and system requirement analysis in the future.

No major issues or deviations are to be reported.

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GLOSSARY

Acronym	Signification
4DT	4-Dimensional Trajectory
ADS-B	Automatic Dependent Surveillance-Broadcast
AIM	Aviation Information Management department
ATC	Air Traffic Control, Air traffic Control
ATCO	Air Traffic Control Operator
ATFMC	Air Traffic Flow Management Center
ATM	Air Traffic Management
CTA	Calculated Time of Arrival
ELDT	Estimated Landing Time
EPP	Extended Projected Profile
ETA	Estimated Time of Arrival
MBSE	Model-Based System Engineering
NOTAM	Notice(s) to Airmen
SysML	Systems Modeling Language
TBO	Trajectory-Based Operations
TOD	Top of Descent

1. INTRODUCTION

1.1. PURPOSE OF THE DOCUMENT

This document provides the Report about Validation of ATM Architecture of Greener Air Traffic Operations within GreAT MWP2- Concept of greener TBO operations. It describes the detailed validation methodology, process and results.

1.2. INTENDED READERSHIP

The intended audience for this document are all the partners involved in GreAT including Commission Services.

1.3. STRUCTURE OF THE DOCUMENT

This document describes the activities to be performed in the validation of greener ATM architecture within GreAT project MWP2- Concept of greener TBO operations.

The structure of the document is as follows:

- **Chapter 1 "Introduction"** describes the purpose and scope of the document, the intended audience, and the document structure;
- **Chapter 2 "Validation contents"** briefly summarizes MBSE methodology and the modeling process of greener ATM operation architecture based on MBSE, and lists the validation objectives of this report;
- **Chapter 3 "Validation approach"** describes the joint simulation platform used in validation activities, provides the validation approach design (including validation metrics, criteria and framework), and describes the simulation scenarios on which the validation depends in phases;
- **Chapter 4 "Validation process and results"** describes the implementation of validation tasks and the results obtained for different validation objectives.

2. VALIDATION CONTENTS

2.1. OVERVIEW OF GREENER ATM OPERATION ARCHITECTURE

2.1.1. OVERVIEW OF MODEL-BASED SYSTEM ENGINEERING METHODS

The greener ATM system is a typical complex system with the following characteristics: 1) multi-agent, multi-business and multi-node, involving the mutual coordination and information interaction of multiple subsystems such as aircraft, satellite and ground stakeholders; 2) each subsystem can play its own role and operate independently of other systems; 3) the ATM system is a dynamic system, including a large number of evolutionary or emergent behaviours; 4) there is a central radiation or distributed network topology among the nodes, which defines the connection between these nodes; 5) effective research on ATM system requires comprehensive knowledge across various research areas, including engineering, economy, policy, operation, etc. To sum up, complex system engineering methods need to be adopted for the analysis and research of ATM systems. The traditional document-based system engineering method extracts information from massive documents, and different designers tend to have divergence in understanding, thus requiring excessive iterative processes and being against the tracking and management of information. Model-based System Engineering starts from requirement analysis, and realizes traceable and verifiable system development process through the continuous evolution of models rather than documents. By using the object-oriented, graphical and visualized system modelling language to describe the system, the ambiguity caused by documents can be avoided, and the functions and behaviors of the system can be reflected more clearly and accurately. These methods have the advantages of high efficiency for understanding and communication, convenient data acquisition, good traceability of technical state, integration of design and validation, etc. Therefore, in recent years, Model-based System Engineering has become a hot topic of research and application in aviation and aerospace system development.

2.1.2. OVERVIEW OF MODELING PROCESS OF MBSE-BASED GREENER ATM OPERATION ARCHITECTURE

The method of Model-based System Engineering is used to forward design the 4DT-based ATM operation systems, describing typical operation scenarios, and capturing the top-level requirements and operation intentions of these systems. Meanwhile, based on this and whereby the Model-based System Engineering methodology, the mission objectives and operational nodes are sorted out and the system composition and system functions are defined, thus a series of 4DT-based ATM architecture models are built to complete the system architecture design.

The general modeling process is shown in Fig. 1. Models such as the high-level operational concept diagram, operational node connection description, operational activity model, operational event trace description, operational state transition description, system interface description, system function description, system event trace description, and system state transition description are built successively.

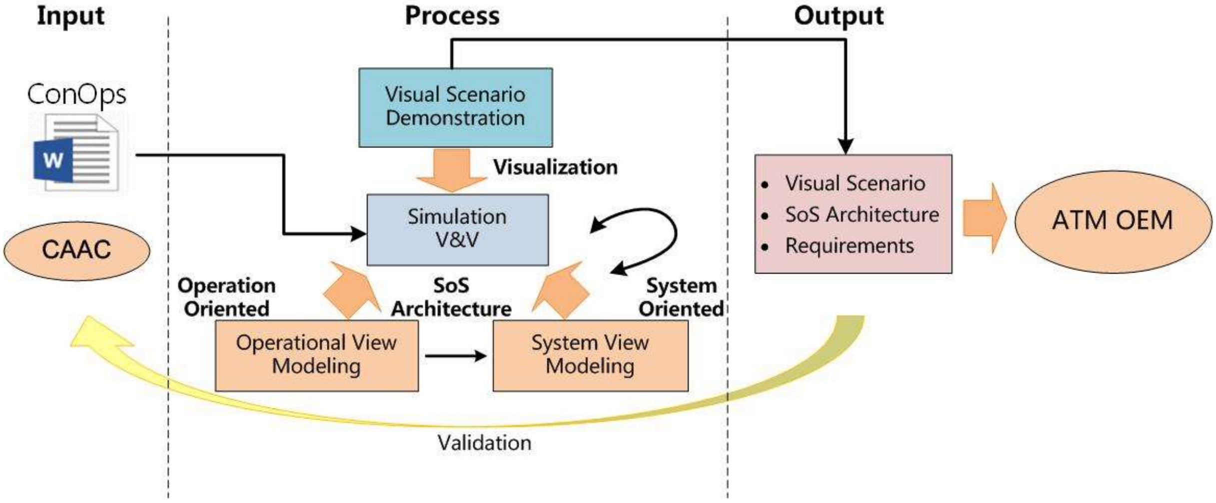


Fig. 1 Modeling Process of MBSE-based Greener ATM operation Architecture

The operational view describes the operational node, the operational mission objectives, and the information that must be exchanged to achieve the objectives. Meanwhile, it also describes the types of information exchange, the frequency of information exchange, and the tasks and operational activities supported by information exchange.

The high-level operational concept diagram describes the environment of the ATM architecture system and the interaction between the architecture and external systems, which can be represented by images, graphics or texts. The 4DT-based operation covers the trajectory planning, trajectory coordination, trajectory execution and trajectory sharing in the whole flight process from the preparation of flight plan before take-off to the landing and the taxiing into the apron. Based on the flight status of an aircraft, the flight process can be divided into nine phases: flight planning, taxi-out, take-off, climbing, cruising, descent, approach, landing and taxi-in. These flight phases are regarded as the target of 4DT-based ATC operations. The operational nodes involved in all task objectives include: aircraft, ATC Operation Management Center, airport, area control center, approach control center, tower control center, airline, weather service department, aviation information management and air traffic flow management center. The connecting line indicates the dependency between operational nodes and mission objectives. The completion of each mission requires the interaction and cooperation between these operational nodes.

The operational activity model is mainly described as a series of activities that need to be performed to complete the mission objectives. It is composed of modeling elements such as operational nodes, operational activities, input and output flows between activities, etc., and reflects the hierarchical relationship and the information flow. Each mission objective corresponds to a separate operational activity model.

Operational event trace description describes the sequence events and time sequence of operational activities, incorporating the dynamic characteristics of nodes. It is realized by the sequence diagram in SysML, and the exchange between system nodes must follow the causal sequence relationship. Compared with the operational activity model, it adopts another form of expression, which describes in more detail the state of each related operational node and the information interaction among them when performing each task.

Operational interface description is used to describe the required operational activities of operational nodes and the information flow exchanged between nodes from the perspective of realizing mission objectives. It mainly displays the related operation and event messages obtained by all operational nodes from operational event trace diagram, as well as the cross-linking relationship among each operational node, and defines the corresponding interface, through which the information exchange between nodes can be realized.

Operational state transition description is implemented via SysML state diagram, which emphasizes dynamic behaviors of the system and is the basis of generating executable models. Its basic elements include state, transition, event and operation. Each pair of trigger-response message and the activities performed in the sequence diagram correspond to a transition on the state machine, and the adjacent transitions must correspond to a state. When these states are expressed, a state machine is completed.

2.2. VALIDATION OBJECTIVES

2.2.1. CONSISTENCY OF MODEL DATA

Consistency validation is a very important step in system architecture development, and its purpose is to avoid conflicting descriptions in architecture design. Consistency includes intra-model consistency and inter-model consistency. Intra-model consistency refers to the attributes of a single model, which means that all elements in the same model meet the syntactic and semantic requirements. The greener ATM operation architecture models and system architecture models built in WP2.2 provide a variety of views to model greener ATM operation systems, ranging from structure to behavior, which are interrelated. The expression of the same information in each view must be consistent, without conflict and redundancy. For example, the events in the operational event trace description must be consistent with the related operational activities in the operational activity model. Prior to the dynamic execution of an executable model, the architecture modelling tool will automatically analyze the consistency of the model, and report errors such as inconsistency of interaction between entity data, which can save a lot of time and energy for manual inspection.

2.2.2. ACTIVITY-TO-FUNCTION TRACEABILITY

Traceability is expressed in different ways according to different context. But the core theme running through various expressions is unique, that is, the complete chain and access of information. The complete chain focuses on the requirement that the product can be traced back to its source, whether the source is physical place, supplier organization, requirements, meeting minutes or various standards and specifications. The model traceability, described in this document, refers to the cross-linking relationship from the functions of systems and subsystems in the system architecture to the operational activities in the operation architecture. Traceability requires that any system function must be traced back to a certain operational activity, indicating that the operational activity is supported by the system function. If a system function cannot be traced back to any operational activity, it is considered redundant. The association between system functions and operational activities need not be a one-to-one mapping. A system function can support multiple operational activities, and vice versa, an operational activity can also be supported by multiple system functions. The relationship between them can be illustrated by the function-to-activity traceability matrix, which clarifies how the operation requirements are transformed into purposeful behaviors.

2.2.3. CONFORMANCE BETWEEN ARCHITECTURE AND CONCEPT

The purpose of model-based architecture development in WP2.2 is to systematically and structurally describe the concept of greener air traffic operation proposed in WP2.1. Analyze and verify whether the operational activities and operational node behavior logic of architecture design are consistent with the operational process based on new concepts expected by stakeholders, which is essential to judge the success of architecture development. Meanwhile, the validation objective also needs to exclude unexpected terminations, dead loops, or resource contention within the architectural model. Executable dynamic models and visualized scenario simulation platforms are the preconditions to ensure the feasibility of this validation. By comparing the dynamic execution process of the model with visualized scenario simulation, we can verify whether the logical design of the operational concept is correct, whether the activities and information interactions described in the operation architecture model are executed in the expected order, and whether the execution of the model is consistent with the designed operational concept.

3. VALIDATION APPROACH

3.1. FUNCTIONAL DESCRIPTION OF JOINT SIMULATION PLATFORM

The joint simulation platform, supporting the validation of greener ATM architecture, is composed of SysML-based architecture modeling tools, visualized scenario simulation tools and data interaction modules.

As a system engineering modeling language, SysML can be used to build requirements models and discrete models. The SysML-based architecture modeling tool can trajectory the whole life cycle of the project, provide intuitive requirements capture view and description method, build discrete models via state diagram, sequence diagram and activity diagram, and simulate the development model to generate executable applications. Meanwhile, it provides the animation mode function of operational state diagram, which can demonstrate the state transition effect of the system under different conditions in a more explicit way. As an embedded system modelling tool, it also supports code generation and compilation. Model/code correlation is provided: if the model is modified, the code generated will be automatically modified accordingly; if the code is modified, then the model will be automatically modified to keep the consistency.

Visualized scenario simulation tools can provide vivid 3D dynamic visualized scenarios, accurate charts, reports and other analysis results, which can be used for the analysis and simulation of the whole operation process of ATM systems. The tool has the following capabilities: (1) Provide the position and attitude data, access time, sensor coverage analysis, etc. of each entity in the analysis scenario; (2) The geographical position and spatial position relationship between objects and the position change relationship with time are displayed based on 2D map background and 3D geospatial model (3) Multi-view and multi-window analysis and display capabilities are provided, and the vivid 3D display environment can show every detail of the mission scenario, so that users can conveniently observe the mission execution process.

The data interaction module is a very important functional module in the joint simulation platform, which provides a basic guarantee for the interaction between architecture modeling tools and visualized scenario simulation tools. It provides a quick way to connect simulation scenarios by using client/server mode. The data interaction module is designed to provide a communication routing for architecture modeling tools to send instructions to the scenario simulation engine and receive data. After receiving the correct command, the visualized scenario simulation tool will generate a processing report or output information according to the settings after internal processing.

The data interaction module includes three elements: data source input, control, and calculation & storage & display. The data source input part is responsible for importing the aircraft trajectory data (such as flight number, longitude, latitude, altitude, speed and other parameters), 3D model data and 3D terrain data into the database to facilitate program call; The visualized platform is responsible for connecting and communicating with the communication module of the visualized simulation software, sending commands and receiving the returned data, and closing the connection interface after the communication; The calculation, storage and display part is responsible for receiving the control instructions sent by the visualized platform, calculating the input data according to the corresponding requirements, and performing simulation demonstration through integrated information, graphic window and standard data file output.

3.2. VALIDATION METHOD DESIGN

3.2.1. VALIDATION METRICS

The validation metrics of greener ATM architecture are shown in the following table:

Table 1 Validation Metrics of Greener ATM architecture

Metrics	**Type**	**Validation method**
The semantics and syntax of the greener ATM architecture model are correct.	Qualitative	Compilation and execution of executable model
The greener ATM architecture model meets the consistency requirements of information and data.	Qualitative	Compilation and execution of executable model
The greener ATM architecture model meets the traceability requirements between system functions and operational activities.	Qualitative	Activity-to-function traceability matrix inspection
Conformance of ATM architecture with greener operation concepts	Qualitative	Joint simulation demonstration of architecture model and operation scenario

3.2.2. VALIDATION CRITERIA

3.2.2.1 CRITERION FOR DATA CONSISTENCY

The executable code compiles without error.

3.2.2.2 CRITERION FOR ACTIVITY-TO-FUNCTION TRACEABILITY

Each function in the function-to-activity traceability matrix can correspond to the related operational activity with no isolated operational activity or function.

3.2.2.3 CRITERION FOR CONFORMANCE BETWEEN MODEL AND OPERATIONAL CONCEPT

Event triggering and state transition, during the execution of the state transition model, are consistent with the operational procedure in the designed scenario. No logic error is detected.

3.2.3. VALIDATION FRAMEWORK

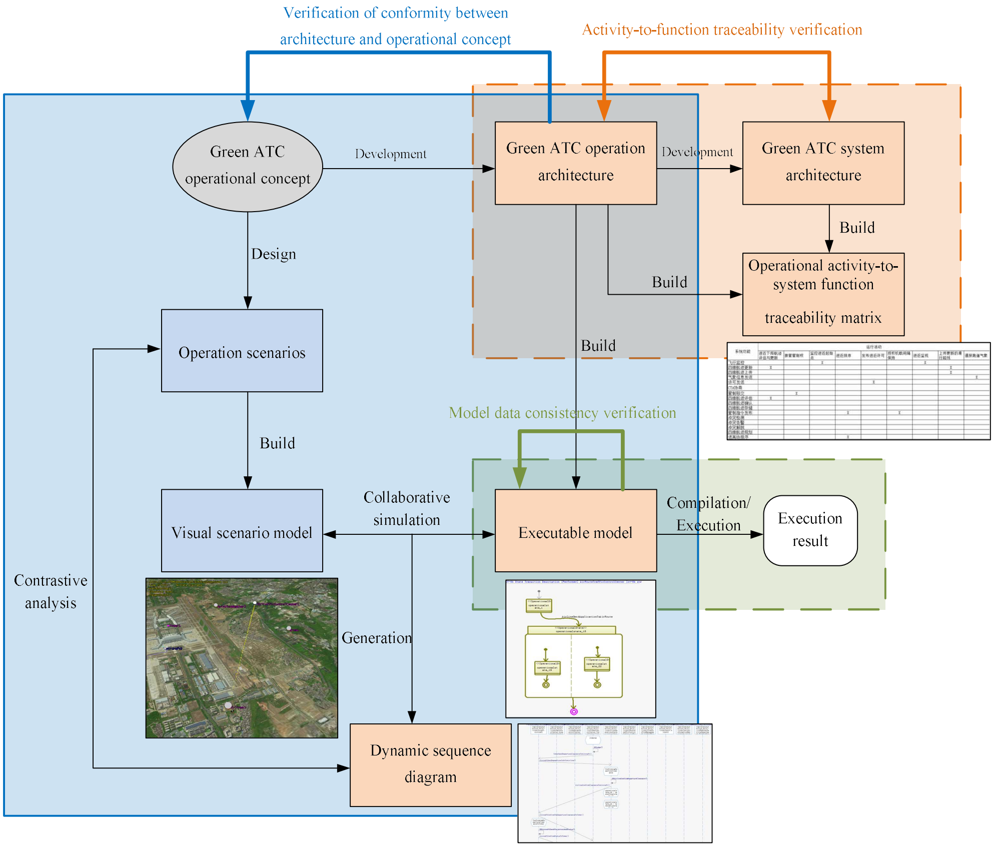


Fig. 2 Framework of greener ATM architecture validation

Fig. 2 indicates the framework of greener ATM architecture validation. Based on the concept of greener ATM operation, scenario analysis and MBSE method are used to describe the greener long-haul operation from the perspectives of scenario and architecture separately, forming a series of validation elements. Among them, the architecture components (orange boxes) adopt the modeling process outlined in Section 2.1.2, and the SysML-based architecture modeling tool is used to develop the greener ATM operation architecture and system architecture models. They describe the operational activities in the ATM system for the purpose of fuel saving and emission reduction and the air/ground system functions supporting the operational activities, and thus construct the activity-to-function traceability matrices. In addition, the greener ATM operation architecture includes the executable models of operational node state machine, which is the key element for dynamic simulation validation of the architecture. The scenario components (blue boxes) design a typical operation scenario by analyzing the concept of greener ATM operation, and build scenario models in the visualized scenario simulation tool. The executable models and the visualized scenario models can be fast-simulated via the data interaction module. In this process, the executing of the executable model will automatically generate a dynamic sequence diagram to show the interactive behaviors of the system during the simulation.

Based on the above validation elements, the following validation activities can be performed for the three objectives in Section 2.2: (1) Generating code from executable model, compiling and executing it, and then validating the data consistency of architecture model according to the results; (2) Checking the corresponding relationship between operational activities and system functions in the activity-to-function traceability matrices, validating the activity-to-function traceability; (3) Performing coordinated simulation demonstration of executable models and visualized scenario models, monitoring and inspecting the simulation process, making comparison and analysis of the generated dynamic sequence diagram with the operation scenario to validate the consistency between the architecture and the operational concept. The validation process and results are described in detail in Chapter 4.

3.3. SIMULATION SCENARIO DESIGN

3.3.1. OVERVIEW OF SIMULATION SCENARIO

The simulation scenario used to validate the architecture of greener ATM system in this document is designed on the basis of the concept of greener air traffic operation described in D2.1

To meet the requirements of fuel saving and emission reduction, the greener operation first needs the air traffic management process that supports trajectory-based operation. Trajectory-based operation (TBO) is based on the mastery of the 4DTs of all aircrafts in the airspace, especially the future trajectories to be flown. It can accurately predict the waypoints and corresponding times of aircrafts flying from take-off to landing, and detect the conflicts between different flight trajectories. Through this technology, the 4DT prediction and management in the terminal area can be realized, so that the control operation situation in the whole airspace can be fully under control, and the flight conflicts can be reduced or even avoided as early as possible. The control efficiency in the airspace can also be improved to a higher level. Compared with the ATM systems driven by the advances of information technology such as communication, navigation and surveillance, TBO is characterized by innovation-driven of ATM concept and operation technology, with information sharing, coordinated decision-making and trajectory management as the core, and being more refined, flexible and efficient. Under the mode of trajectory-based operation centered with the 4DTs of the whole flight cycles of aircrafts, ATC authorities, airlines and aircrafts share, negotiate and manage dynamic trajectories to realize the whole process integration of flight planning and flight implementation. Meanwhile, data link technology is used to realize the digital coordinated air-ground control. Therefore, the aircraft flight activities and air-ground interaction during the whole flight cycle, covering flight planning, taxi-out, take-off, climb, cruise, descent, approach, landing & taxiing and taxi-in, in the simulation scenario are all designed according to the operation requirements of TBO.

In this document, an international flight from Guangzhou Baiyun International Airport to Amsterdam Schiphol International Airport is taken as the simulation scenario (in line with long-haul operation research activities in MWP3), covering the whole flight phase from flight planning to taxi-in.

3.3.2. SIMULATION SCENARIO DESCRIPTION BY PHASES

3.3.2.1 FLIGHT PLANNING PHASE

- The airline applies for a flight from the ATC Operation Management Center.
- The ATC Operation Management Center issues the airspace status and use restrictions to the airline and ATFMC;
- ATFMC sends traffic flow management strategy to the airline;
- The airline will confirm with ATFMC after evaluation;
- The ATFMC updates and issues the planned trajectory, sends it to the airlines, the weather service department and the tower control center;
- The weather service department issue the meteorological message to the tower control center;
- The weather service department sends NOTAMS to the tower control center;

- The airline submits TOBT to the tower control center;
- The tower control center control center allocates the taxi path and uploads the departure trajectory message to the aircraft;
- After receiving the departure trajectory message, the aircraft calculates the departure trajectory and transmits it to the tower control center control center;
- The tower control center sends the departure trajectory received to ATFMC, airport, area control center and approach control center;
- ATFMC, airport, area control center and approach control center jointly participate in negotiation and then feed back to the tower control center;
- The tower control center updates the departure trajectory;
- The tower control center uploads the updated departure trajectory to the aircraft, ATFMC, airport, area control center and approach control center;
- Aircraft, ATFMC, airport, area control center and approach control center confirm and store the updated departure trajectory.

3.3.2.2 TAXI-OUT PHASE

- The aircraft checks the trajectory and status of the aircraft;
- The aircraft sends a departure clearance request to the tower control center;
- The tower control center issues the departure clearance to the aircraft;
- The aircraft sends departure information to the airline;
- The airline feeds back the aircraft after confirmation;
- The aircraft sends a push-out clearance request to the tower control center;
- The tower control center issues the push-out clearance to the aircraft;
- The aircraft confirms the clearance.
- The aircraft starts taxiing;
- The tower control center monitors the trajectory conformance during aircraft taxiing phase;
- ATFMC predicts and monitors the capacity-demand balance in the terminal area;
- The tower control center requests capacity/demand message from ATFMC;
- The ATFMC analyzes the capacity/demand balancing and sends the results to the tower control center, then assigns the arrival time of the flight;
- The aircraft continues to taxi to the runway threshold according to the new taxi path.

3.3.2.3 DEPARTURE PHASE

- The aircraft arrives at runway threshold;
- The tower control center issues the runway entering clearance to the aircraft;
- The aircraft confirms the clearance and enter the runway;

- The tower control center issues a take-off clearance to the aircraft;
- The aircraft starts to take off;
- The tower control center transfers control to the approach control center;
- The aircraft confirms the control transfer, joins the departure flow, and then starts climbing.

3.3.2.4 CLIMBING PHASE

- The approach control center continuous the monitoring of aircraft climbing;
- After confirming the required flight altitude, the approach control center transfers the control to the area control center.
- The area control center takes over control;
- The aircraft confirms the control transfer with the approach control center;
- The aircraft enters the cruising phase after reaching the cruising altitude.

3.3.2.5 CRUISING PHASE

- The area control center performs aircraft monitoring;
- The airborne system recognizes the wind change at the planned altitude, that is, the change of wind direction and wind speed;
- The aircraft requests to change its flight level and climb to a higher level for the purpose of fuel saving;
- The area control center assesses if the airspace situation allows the flight level change;
- The aircraft receives the clearance of flight level change, obtains the position message of surrounding aircrafts via ADS-B In, and starts the implementation of In Trail Procedure (ITP). The aircraft transmits the latest EPP data to the area control center immediately after the change is completed;
- The area control center updates the ground reference flight trajectory, and issues the updated reference trajectory to the aircraft and ATFMC;
- The aircraft cruises according to the updated reference trajectory;
- ATFMC continuously monitors and manages issues related to air traffic flow;
- The weather service department issues the meteorological message to the area control center;
- The area control center sends the meteorological message to the aircraft;
- After receiving the meteorological message, the aircraft evaluates that there is a meteorological conflict in the following trajectory, thus generates the initial rerouting trajectory and sends it to the airline;
- The airline submits the initial rerouting trajectory to ATFMC;
- ATFMC receives and evaluates the rerouting trajectory, and sends the confirmed

rerouting trajectory to the area control center and the airline;

- The airline receives the rerouting trajectory and feeds it back to the aircraft;
- The aircraft receives the rerouting trajectory, and applies to the area control center for a detour clearance;
- After receiving the request, the area control center issues a detour clearance to the aircraft;
- After receiving the detour clearance, the aircraft recalculates the trajectory and transmits the EPP data;
- The area control center updates the reference trajectory, and issues the updated reference trajectory to the aircraft and ATFMC;
- ATFMC continuously monitors and manages related traffic flow issues;
- The aircraft cruises according to the updated reference trajectory.

3.3.2.6 DESCENT PHASE

- When the aircraft flies close to the terminal area of the arrival airport, the pilot asks the area control center for meteorological and operational messages;
- The area control center requests meteorological and operational messages from the weather service department;
- The weather service department sends meteorological and operational message to the area control center;
- The area control center sends meteorological and operational messages to the aircraft;
- The area control center plans the approach trajectory, and shares the generated approach trajectory with the aircraft;
- The weather service department uploads meteorological and operational message to the aircraft;
- After receiving the meteorological and operational messages, the aircraft develops the initial approach trajectory and transmits the ETA window to the approach control center;
- The approach control center, tower control center, ATFMC negotiate CTA with the area control center;
- The area control center uploads the negotiated CTA to the aircraft;
- The aircraft confirms and updates the trajectory;
- The area control center updates and shares the approach trajectory with the approach control center, tower control center and ATFMC;
- ATFMC shares ELDT with the airport;
- The airport receives the ELDT and sends the allocated aprons to the tower control center;

- The tower control center plans the taxi path, and the area control center uploads the taxi path to the aircraft;
- The aircraft receives the ground taxiing message, and then arrives at TOD;
- The area control center issues a descent clearance to the aircraft;
- The aircraft performs descent operation after confirming the clearance;
- The area control center continuously monitors the descent process of the aircraft, and when the aircraft releases a descent conflict alert, the area control center immediately issues a conflict resolution instruction to the aircraft;
- The aircraft follows the control instructions;
- The area control center updates the descent reference trajectory, while the approach control center and ATFMC participate in the assessment, update and confirmation of the trajectory;
- The aircraft reaches the control transfer altitude;
- The area control center transfers the control to the approach control center of the arrival airport;
- The aircraft confirms the control transfer;

3.3.2.7 APPROACH PHASE

- The approach control center monitors the initial approach fix;
- The aircraft assesses CTA and negotiates the CTA with the approach control center;
- The aircraft adjusts the speed according to CTA;
- The approach control center issues an approach clearance to the aircraft;
- The approach control center authorizes airborne separation maintenance to the aircraft;
- The aircraft starts to approach according to the airborne separation;
- The approach control center continuously monitors the aircraft operations;
- The airport issues the updated apron information to the tower control center;
- The approach control center updates the approach taxi path and uploads the updated taxi path to the aircraft;
- The aircraft confirms the updated taxi path with the approach control center;
- The approach control center informs the aircraft of the runway meteorological message;
- The aircraft completes the final approach and prepares for landing;
- The approach control center transfers the control to the tower control center of the arrival airport;
- The aircraft confirms the control transfer.

3.3.2.8 LANDING PHASE

- The tower control center continuously monitors the aircraft operations, while the airport reallocates the runway;
- The aircraft receives the updated runway message and issues a landing clearance request to the tower control center;
- The tower control center issues the landing clearance to the aircraft;
- The aircraft confirms the landing clearance, lands on the runway, and then arrives at the runway threshold.

3.3.2.9 TAXI-IN PHASE

- The aircraft leaves the runway;
- The tower control center issues a taxi-in clearance to the aircraft;
- The aircraft confirms the taxi-in clearance and enters the taxiing phase;
- The tower control center monitors the taxiing phase and issues the parking clearance to the aircraft;
- The aircraft confirms the parking clearance and enters the apron.

4. VALIDATION PROCESS AND RESULTS

4.1. MODEL DATA CONSISTENCY VALIDATION

4.1.1. EXECUTABLE MODEL OF THE OPERATION ARCHITECTURE

Generally, the SysML-based architecture models developed in WP2.2 can be divided into static models and dynamic models. The static model represents the logical relationship of system structure, organization, information connection, etc. The dynamic model represents the message interaction between the system and activities, and reflects the dynamic characteristics of the system. Only when the dynamic model is developed into an executable model, the dynamic characteristics of the system can be revealed during the execution of the simulation. In the greener ATM operation architecture models, the state diagram model realizes the model execution states and transitions. It is the core of executable models, and other models provide supports such as operations, signals and data messages.

The state diagram models are developed based on the information provided by the operational interface models and the operational activity models. Due to the limited space, only the state diagram model of aircraft node from flight planning phase to climbing phase of the greener ATM operation architecture is taken as an example (as shown in Fig. 3). The complete state diagram model includes the initial state, the transitional operational states, the events triggering the state transition and the terminal state. The model fully describes the dynamic behavior sequence of the aircraft from the flight planning before takeoff to the process of taxi-out, take-off and climbing.

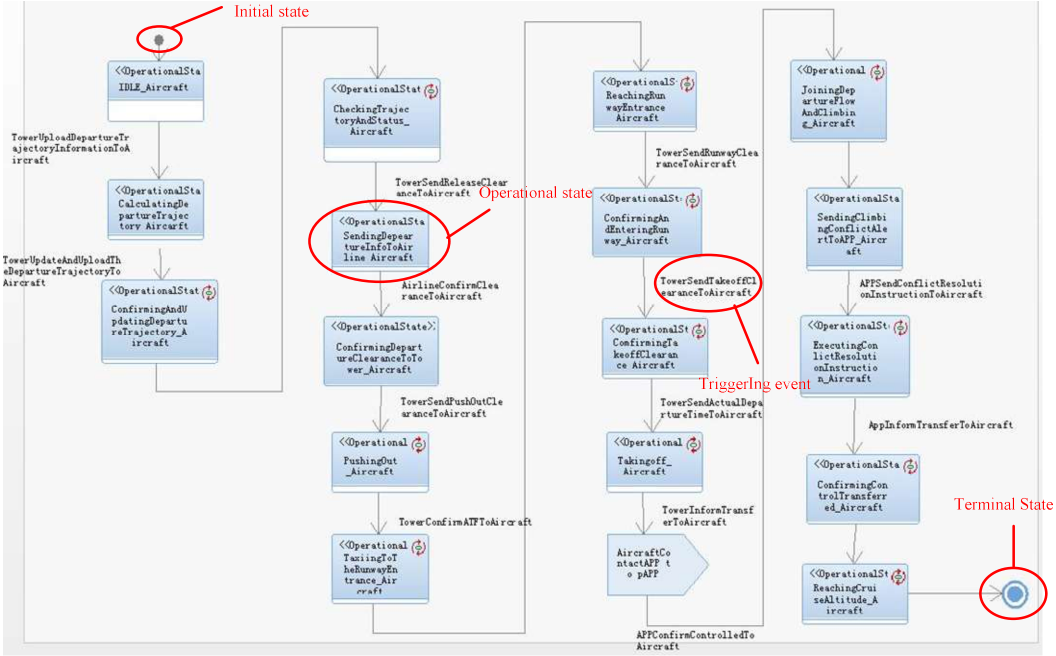


Fig. 3 State diagram model of aircraft node during the flight planning - climbing phases

4.1.2. VALIDATION RESULTS

Based on the state diagram model, the architecture modeling tool used in this document can automatically generate executable code via compilation to validate the consistency of the internal data of the model and drive the subsequent coordinated simulation. If the syntax of the model and programming is correct and the internal data is consistent and complete, the code can be executed, otherwise the code generation will fail.

The compilation results of a complete set of state diagram models of the developed greener ATM architecture model are as follows:

```
All checks terminated successfully.


Checker completed
0 errors, 0 warnings


Code generation      D:\GreAT_models\WP2.3\20220627\DefaultComponent\DefaultConfig
directory:

Code generation completed


0 errors, 0 warnings, 0 messages
```

Fig. 4 Compilation results of executable model of greener ATM architecture

Therefore, the architecture model meets the requirements of data consistency.

4.2. ACTIVITY-TO-FUNCTION TRACEABILITY VALIDATION

4.2.1. ACTIVITY-TO-FUNCTION TRACEABILITY MATRIX

The activity-to-function traceability matrix focuses on the linkage between the system functions described in the system architecture model and the operational activities described in the operational architecture model, depicting the mapping between the system functions (or the ability and executor to provide system functions) and the operational activities, and clarifying how the operational requirements are transformed into purposeful behaviors (performed by the system or solution).

The activity-to-function traceability matrix illustrates the relationship between a set of operational activities and system functions applied in the architecture description. The relationship between activities and system functions can be many-to-many (that is, an activity may be supported by multiple functions, and a function may also support multiple activities). Generally, the matrix indicates the requirement tracing of operational activities on one axis, and the system functions on the other axis. The cell where the two axes intersect can be marked with an "X", a date or a phase according to specific conditions.

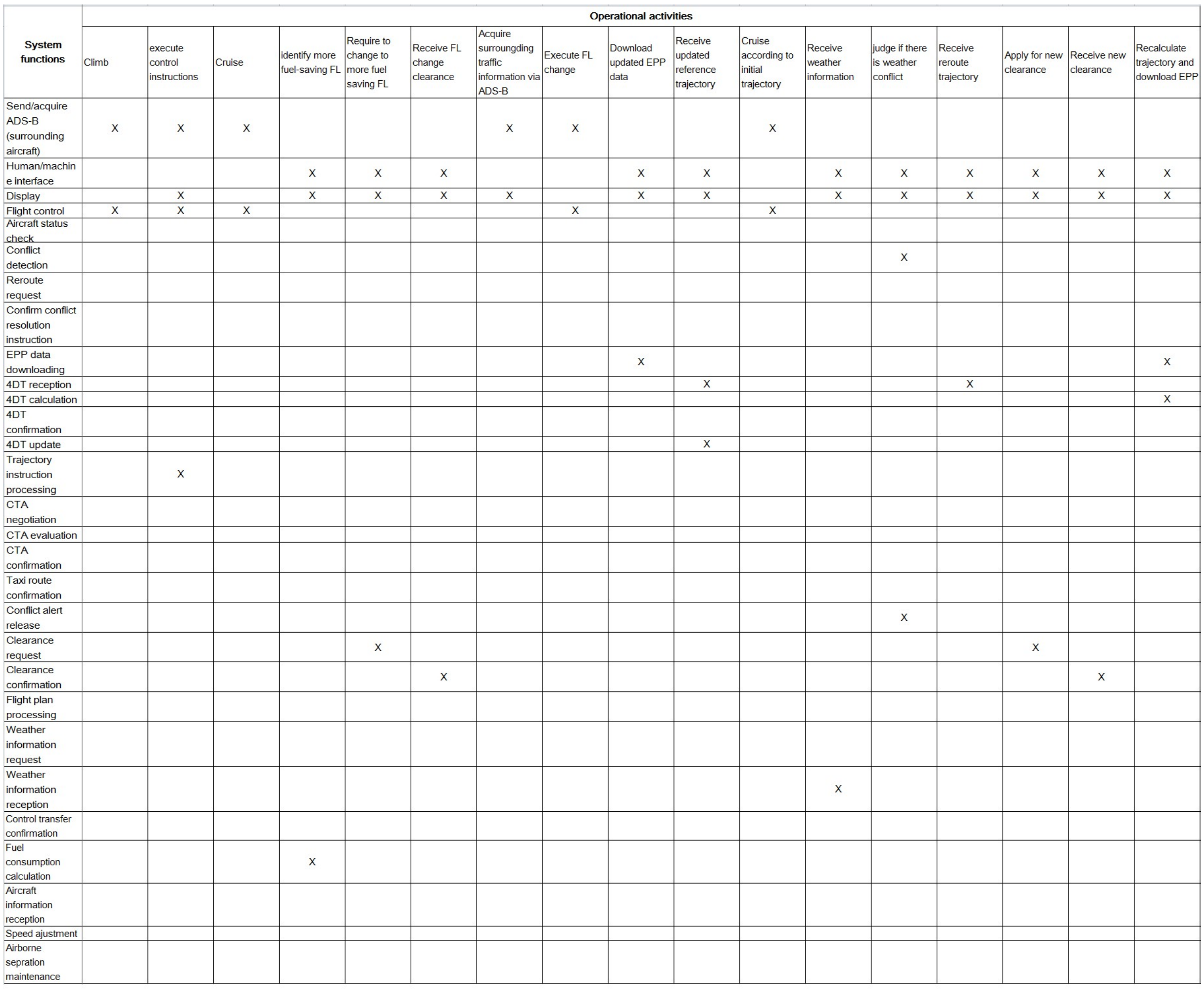
For the purpose of expressing clearly and reducing matrix complexity, this section divides the traceability matrix of the whole greener ATM architecture into multiple sub-matrices per operational nodes. Each submatrix represents the crosslinking relationship between the system functions of the operational node and the operational activities performed by that node. The corresponding relationship is indicated by an "X" mark.

4.2.1.1 AIRCRAFT

The activity-to-function traceability matrix of the aircraft node is shown in Fig. 5~ Fig. 8.

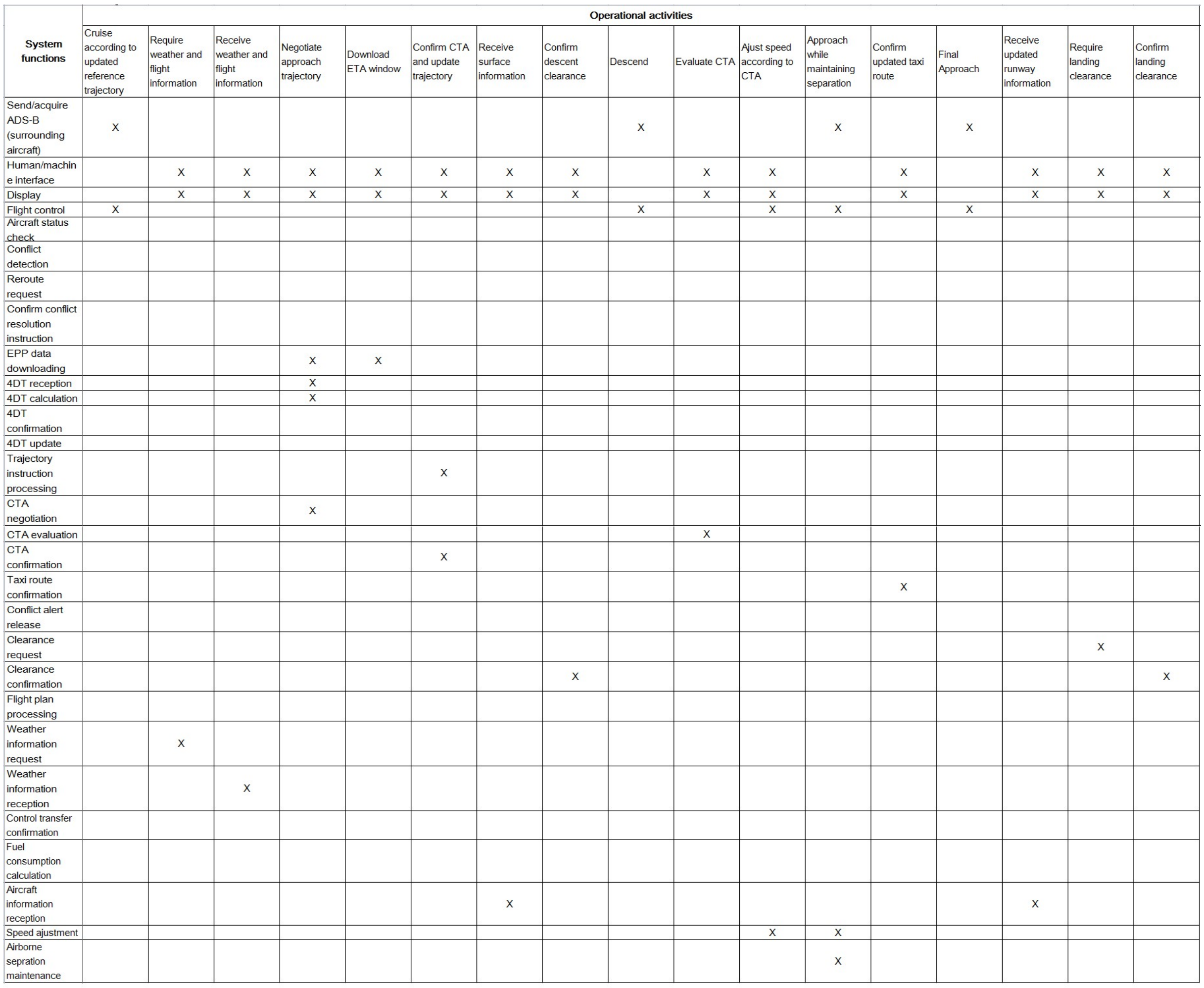
System functions	Operational activities																
	Departure trajectory calculation and downloading	Departure trajectory confirmation and update	Request departure clearance	Confirm departure clearance	Check trajectory and aircraft status	Confirm push-out clearance	Push out	Confirm taxi-out clearance	Taxi out	Judge if there is traffic conflict	Acquire updated taxi route	Keep taxiing to the runway entrance	Confirm take-off clearance	Enter the runway	Take off	Confirm control transfer	Join the departure flow
Send/acquire ADS-B (surrounding aircraft)							X		X	X		X		X	X		X
Human/machine interface	X	X	X	X	X	X		X		X	X		X			X	
Display	X	X	X	X	X	X		X			X		X			X	
Flight control							X		X			X		X	X		X
Aircraft status check					X												
Conflict detection										X							
Reroute request																	
Confirm conflict resolution instruction																	
EPP data downloading	X																
4DT reception																	
4DT calculation	X																
4DT confirmation		X									X						
4DT update		X									X						
Trajectory instruction processing																	
CTA negotiation																	
CTA evaluation																	
CTA confirmation																	
Taxi route confirmation																	
Conflict alert release										X							
Clearance request			X														
Clearance confirmation				X		X		X					X				
Flight plan processing	X																
Weather information request																	
Weather information reception																	
Control transfer confirmation																X	
Fuel consumption calculation																	
Aircraft information reception																	
Speed ajustment																	
Airborne sepration maintenance																	

Figure 5 Activity-to-function traceability matrix of the aircraft node (a)



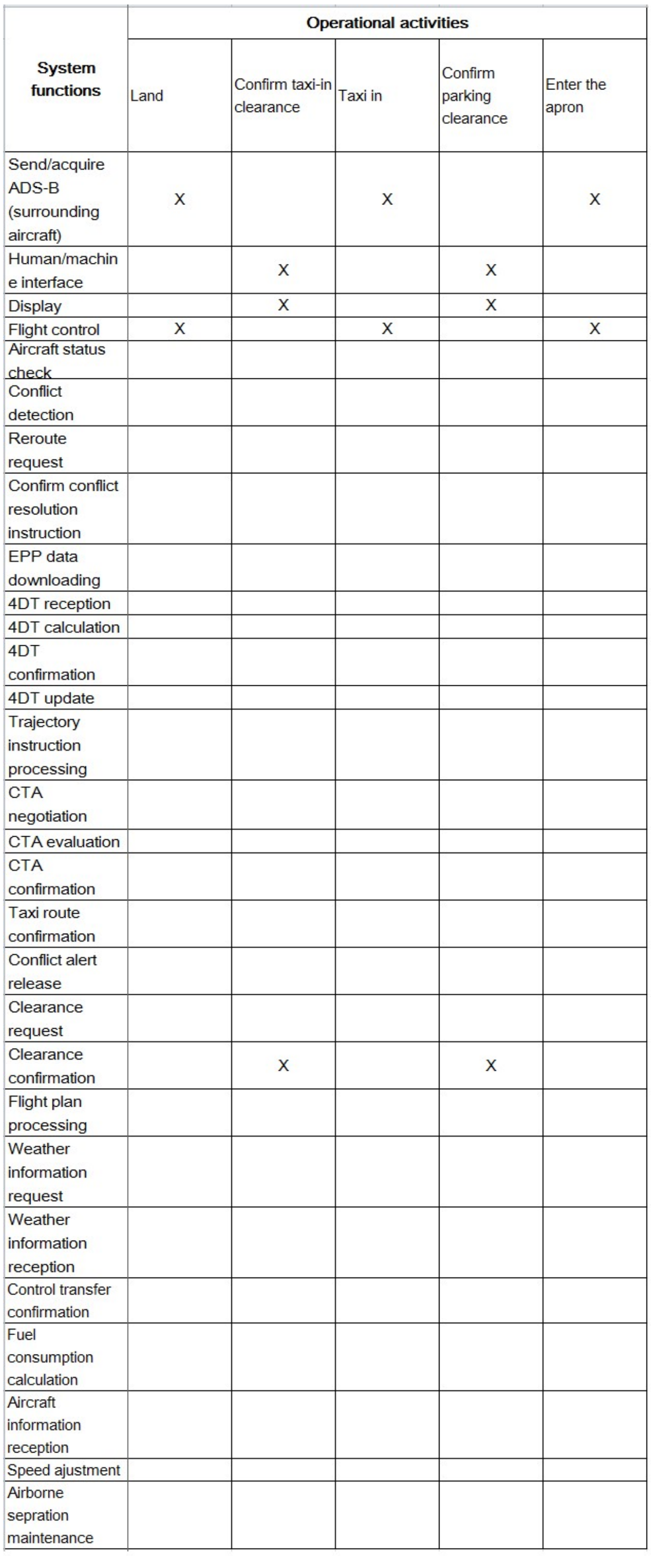
System functions	Operational activities																
	Climb	execute control instructions	Cruise	identify more fuel-saving FL	Require to change to more fuel saving FL	Receive FL change clearance	Acquire surroungding traffic information via ADS-B	Execute FL change	Download updated EPP data	Receive updated reference trajectory	Cruise according to initial trajectory	Receive weather information	judge if there is weather conflict	Receive reroute trajectory	Apply for new clearance	Receive new clearance	Recalculate trajectory and download EPP
Send/acquire ADS-B (surrounding aircraft)	X	X	X				X	X			X						
Human/machine interface				X	X	X			X	X		X	X	X	X	X	X
Display		X		X	X	X	X		X	X		X	X	X	X	X	X
Flight control	X	X	X					X			X						
Aircraft status check																	
Conflict detection													X				
Reroute request																	
Confirm conflict resolution instruction																	
EPP data downloading									X								X
4DT reception										X				X			
4DT calculation																	X
4DT confirmation																	
4DT update										X							
Trajectory instruction processing		X															
CTA negotiation																	
CTA evaluation																	
CTA confirmation																	
Taxi route confirmation																	
Conflict alert release													X				
Clearance request					X										X		
Clearance confirmation						X										X	
Flight plan processing																	
Weather information request																	
Weather information reception												X					
Control transfer confirmation																	
Fuel consumption calculation				X													
Aircraft information reception																	
Speed ajustment																	
Airborne sepration maintenance																	

Figure 6 Activity-to-function traceability matrix of the aircraft node (b)



System functions	Operational activities																
	Cruise according to updated reference trajectory	Require weather and flight information	Receive weather and flight information	Negotiate approach trajectory	Download ETA window	Confirm CTA and update trajectory	Receive surface information	Confirm descent clearance	Descend	Evaluate CTA	Ajust speed according to CTA	Approach while maintaining separation	Confirm updated taxi route	Final Approach	Receive updated runway information	Require landing clearance	Confirm landing clearance
Send/acquire ADS-B (surrounding aircraft)	X								X			X		X			
Human/machine interface		X	X	X	X	X	X	X		X	X		X		X	X	X
Display		X	X	X	X	X	X	X		X	X		X		X	X	X
Flight control	X								X		X	X		X			
Aircraft status check																	
Conflict detection																	
Reroute request																	
Confirm conflict resolution instruction																	
EPP data downloading				X	X												
4DT reception				X													
4DT calculation				X													
4DT confirmation																	
4DT update																	
Trajectory instruction processing						X											
CTA negotiation				X													
CTA evaluation										X							
CTA confirmation						X											
Taxi route confirmation													X				
Conflict alert release																	
Clearance request																X	
Clearance confirmation								X									X
Flight plan processing																	
Weather information request		X															
Weather information reception			X														
Control transfer confirmation																	
Fuel consumption calculation																	
Aircraft information reception							X								X		
Speed ajustment											X	X					
Airborne sepration maintenance												X					

Figure 7 Activity-to-function traceability matrix of the aircraft node (c)

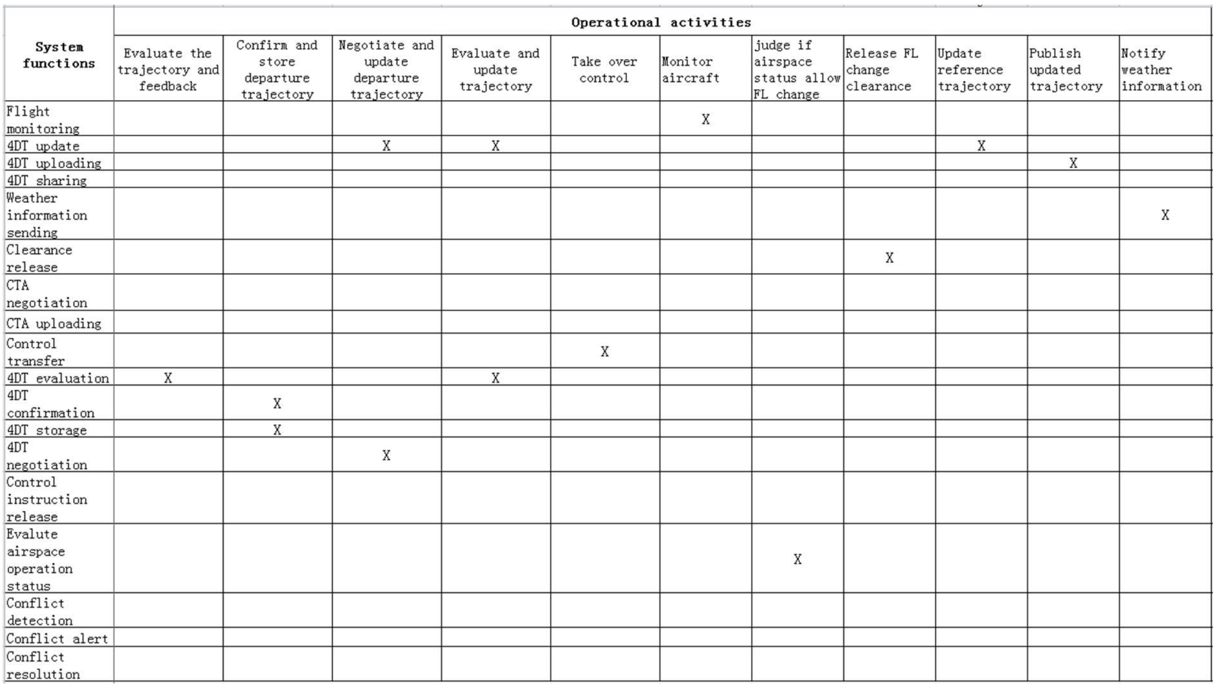


System functions	Operational activities				
	Land	Confirm taxi-in clearance	Taxi in	Confirm parking clearance	Enter the apron
Send/acquire ADS-B (surrounding aircraft)	X		X		X
Human/machine interface		X		X	
Display		X		X	
Flight control	X		X		X
Aircraft status check					
Conflict detection					
Reroute request					
Confirm conflict resolution instruction					
EPP data downloading					
4DT reception					
4DT calculation					
4DT confirmation					
4DT update					
Trajectory instruction processing					
CTA negotiation					
CTA evaluation					
CTA confirmation					
Taxi route confirmation					
Conflict alert release					
Clearance request					
Clearance confirmation		X		X	
Flight plan processing					
Weather information request					
Weather information reception					
Control transfer confirmation					
Fuel consumption calculation					
Aircraft information reception					
Speed ajustment					
Airborne sepration maintenance					

Figure 8 Activity-to-function traceability matrix of the aircraft node (d)

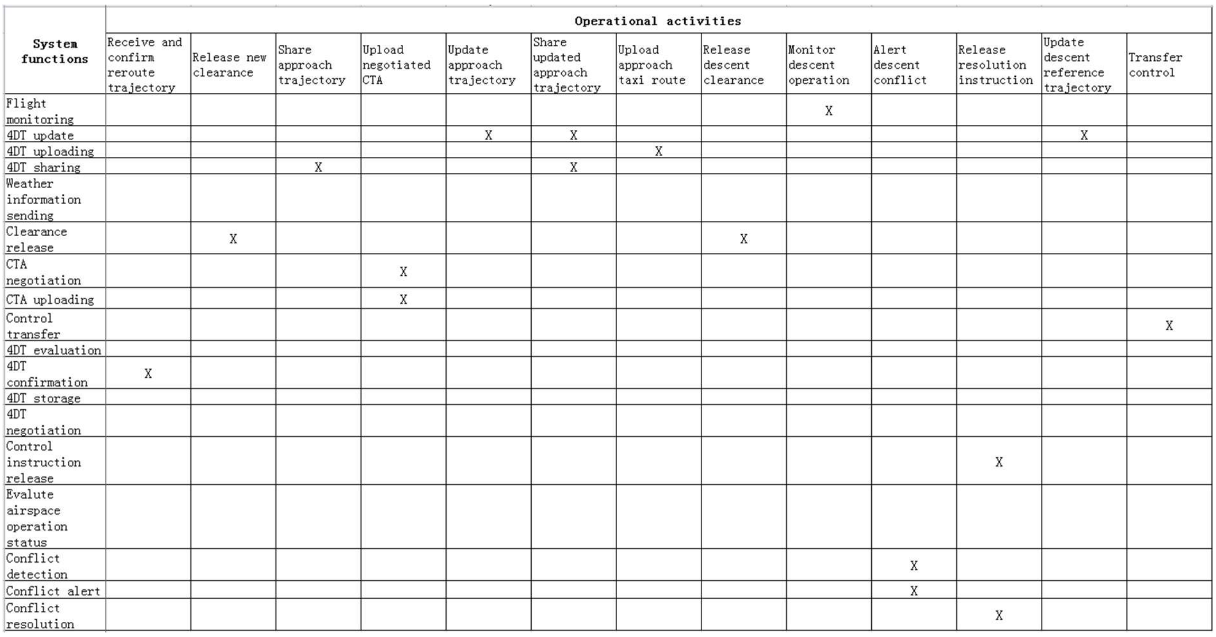
4.2.1.2 AREA CONTROL CENTER

The activity-to-function traceability matrix of the area control center node is shown in Fig. 9~ Fig. 10.



System functions	Operational activities										
	Evaluate the trajectory and feedback	Confirm and store departure trajectory	Negotiate and update departure trajectory	Evaluate and update trajectory	Take over control	Monitor aircraft	judge if airspace status allow FL change	Release FL change clearance	Update reference trajectory	Publish updated trajectory	Notify weather information
Flight monitoring						X					
4DT update			X	X					X		
4DT uploading										X	
4DT sharing											
Weather information sending											X
Clearance release								X			
CTA negotiation											
CTA uploading											
Control transfer					X						
4DT evaluation	X			X							
4DT confirmation		X									
4DT storage		X									
4DT negotiation			X								
Control instruction release											
Evalute airspace operation status							X				
Conflict detection											
Conflict alert											
Conflict resolution											

Figure 9 Activity-to-function traceability matrix of the area control center node (a)

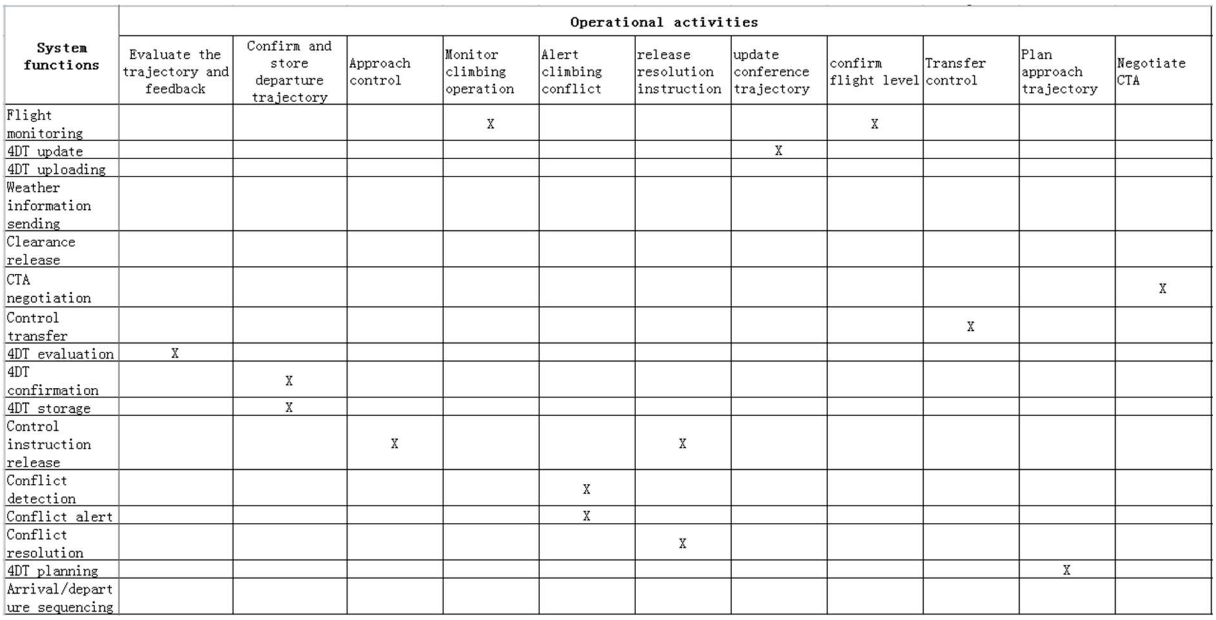


System functions	Operational activities												
	Receive and confirm reroute trajectory	Release new clearance	Share approach trajectory	Upload negotiated CTA	Update approach trajectory	Share updated approach trajectory	Upload approach taxi route	Release descent clearance	Monitor descent operation	Alert descent conflict	Release resolution instruction	Update descent reference trajectory	Transfer control
Flight monitoring									X				
4DT update					X	X						X	
4DT uploading							X						
4DT sharing			X			X							
Weather information sending													
Clearance release		X						X					
CTA negotiation				X									
CTA uploading				X									
Control transfer													X
4DT evaluation													
4DT confirmation	X												
4DT storage													
4DT negotiation													
Control instruction release											X		
Evalute airspace operation status													
Conflict detection										X			
Conflict alert										X			
Conflict resolution											X		

Figure 10 Activity-to-function traceability matrix of the area control center node (b)

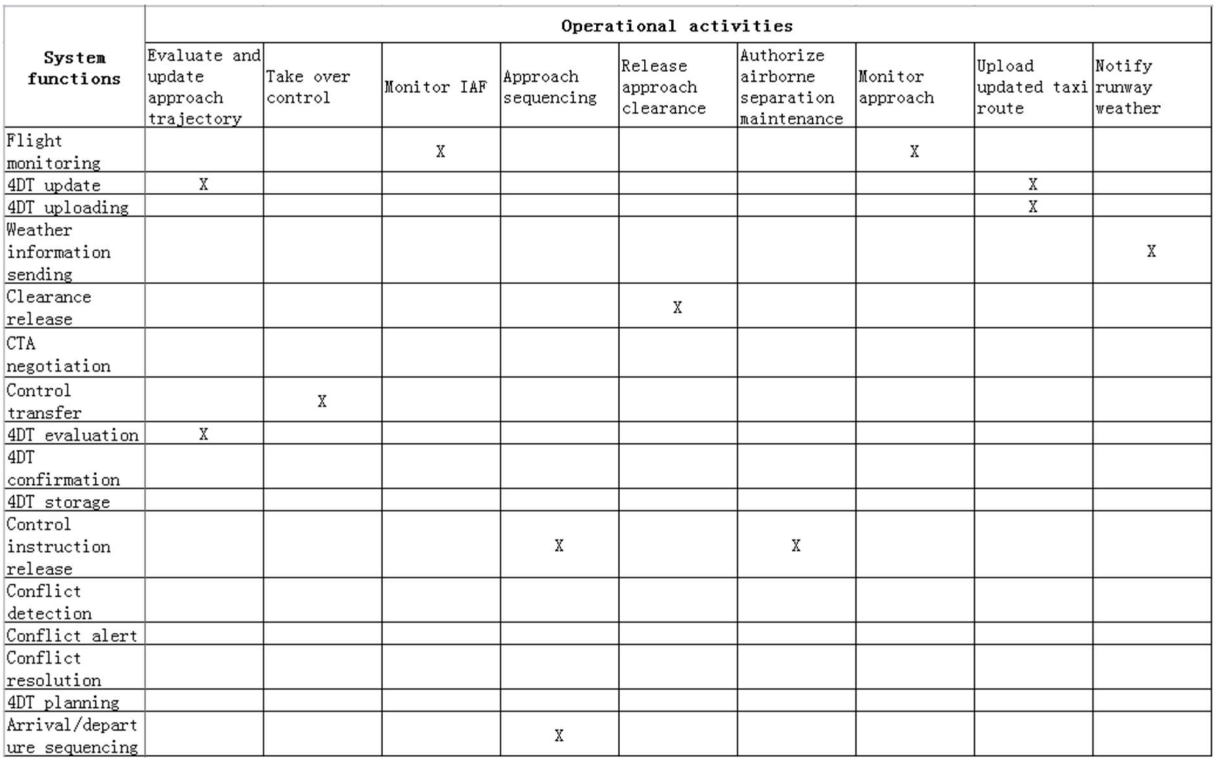
4.2.1.3 APPROACH CONTROL CENTER

The activity-to-function traceability matrix of the approach control center node is shown in Fig. 11~ Fig. 12.



System functions	**Operational activities**										
	Evaluate the trajectory and feedback	Confirm and store departure trajectory	Approach control	Monitor climbing operation	Alert climbing conflict	release resolution instruction	update conference trajectory	confirm flight level	Transfer control	Plan approach trajectory	Negotiate CTA
Flight monitoring				X				X			
4DT update							X				
4DT uploading											
Weather information sending											
Clearance release											
CTA negotiation											X
Control transfer									X		
4DT evaluation	X										
4DT confirmation		X									
4DT storage		X									
Control instruction release			X			X					
Conflict detection					X						
Conflict alert					X						
Conflict resolution						X					
4DT planning										X	
Arrival/departure sequencing											

Figure 11 Activity-to-function traceability matrix of the approach control center node (a)



System functions	**Operational activities**								
	Evaluate and update approach trajectory	Take over control	Monitor IAF	Approach sequencing	Release approach clearance	Authorize airborne separation maintenance	Monitor approach	Upload updated taxi route	Notify runway weather
Flight monitoring			X				X		
4DT update	X							X	
4DT uploading								X	
Weather information sending									X
Clearance release					X				
CTA negotiation									
Control transfer		X							
4DT evaluation	X								
4DT confirmation									
4DT storage									
Control instruction release				X		X			
Conflict detection									
Conflict alert									
Conflict resolution									
4DT planning									
Arrival/departure sequencing				X					

Figure 12 Activity-to-function traceability matrix of the approach control center node (b)

4.2.1.4 TOWER CONTROL CENTER

The activity-to-function traceability matrix of the tower control center node is shown in Fig. 13~ Fig. 14.

System functions	**Operational activities**										
	Assign departure and taxi route	Upload departure trajectory	Negotiate and update departure trajectory	Update and upload departure trajectory	Update and publish departure trajectory	Release departure clearance	Release push-out clearance	Release taxi-out clearance	Monitor operation conformance at taxi phase	Update taxi route	Release take-off clearance
Flight monitoring									X		
4DT update				X	X					X	
4DT uploading		X		X	X						
Runway information confirmation											
Clearance release						X	X	X			X
CTA negotiation											
Control transfer											
4DT confirmation											
4DT negotiation			X								
Control instruction release											
4DT planning											
Runway and taxiway assignment	X										

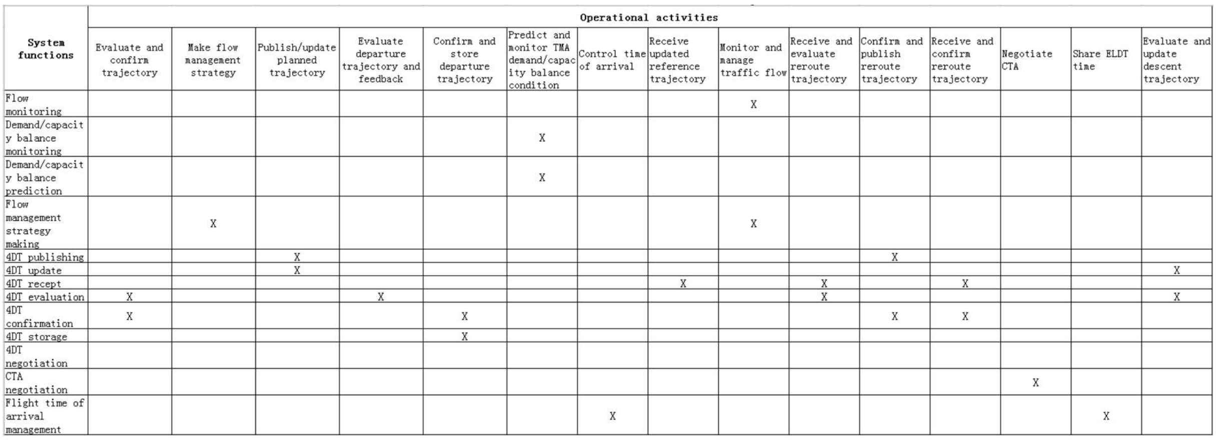
Figure 13 Activity-to-function traceability matrix of the tower control center node (a)

System functions	**Operational activities**									
	Publish actual take-off time	Tranfer control	Negotiate CTA	Plan approach taxi route	Update approach taxi route	Take over control	Monitor aircraft operation	Confirm runway availability	Reassign runway	Release landing clearance
Flight monitoring							X			
4DT update					X					
4DT uploading										
Runway information confirmation								X		
Clearance release										X
CTA negotiation			X							
Control transfer		X				X				
4DT confirmation										
4DT negotiation										
Control instruction release	X									
4DT planning				X						
Runway and taxiway assignment									X	

Figure 14 Activity-to-function traceability matrix of the tower control center node (b)

4.2.1.5 AIR TRAFFIC FLOW MANAGEMENT CENTER

The activity-to-function traceability matrix of the air traffic flow monitoring center node is shown in Fig. 15.

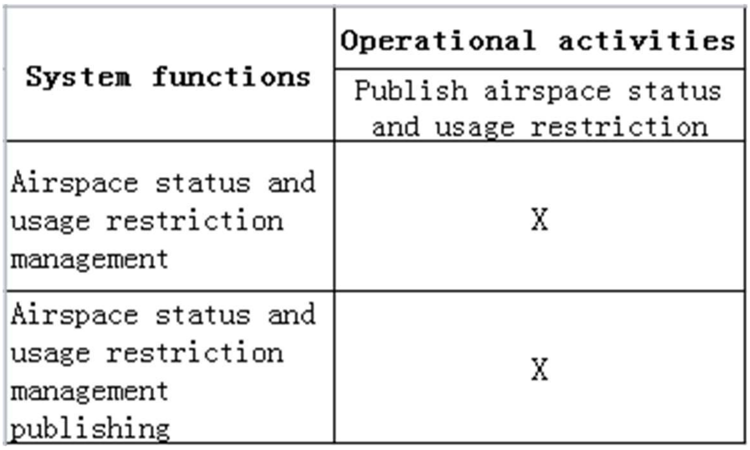


System functions	Operational activities														
	Evaluate and confirm trajectory	Make flow management strategy	Publish/update planned trajectory	Evaluate departure trajectory and feedback	Confirm and store departure trajectory	Predict and monitor TMA demand/capacity balance condition	Control time of arrival	Receive updated reference trajectory	Monitor and manage traffic flow	Receive and evaluate reroute trajectory	Confirm and publish reroute trajectory	Receive and confirm reroute trajectory	Negotiate CTA	Share ELDT time	Evaluate and update descent trajectory
Flow monitoring									X						
Demand/capacity balance monitoring						X									
Demand/capacity balance prediction						X									
Flow management strategy making		X							X						
4DT publishing			X								X				
4DT update			X												X
4DT recept								X		X		X			
4DT evaluation	X			X						X					X
4DT confirmation	X				X						X	X			
4DT storage					X										
4DT negotiation															
CTA negotiation													X		
Flight time of arrival management							X							X	

Figure 15 Activity-to-function traceability matrix of the air traffic flow monitoring center node

4.2.1.6 ATC OPERATION MANAGEMENT CENTER

The activity-to-function traceability matrix of the ATC Operation Management Center node is shown in Fig. 16.

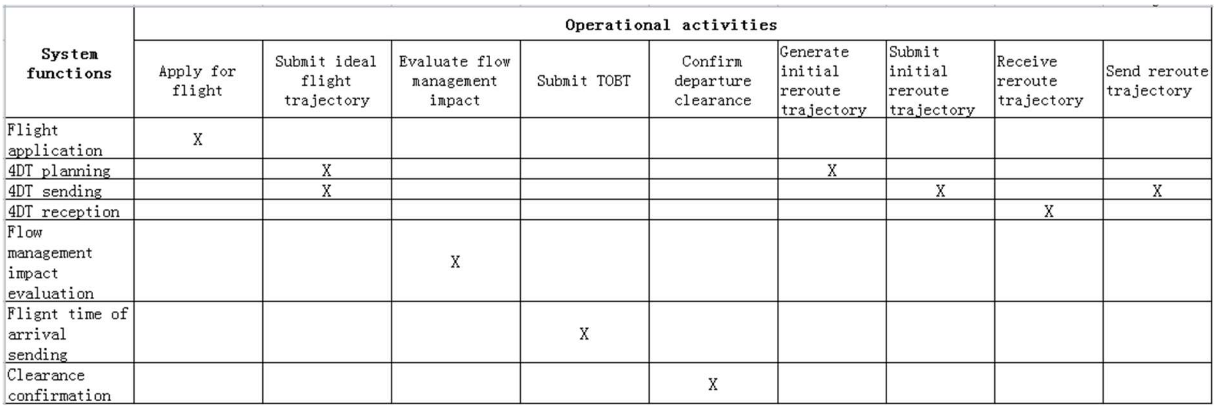


System functions	Operational activities
	Publish airspace status and usage restriction
Airspace status and usage restriction management	X
Airspace status and usage restriction management publishing	X

Figure 16 Activity-to-function traceability matrix of the ATC Operation Management Center node

4.2.1.7 AIRLINE

The activity-to-function traceability matrix of the airline node is shown in Fig. 17.

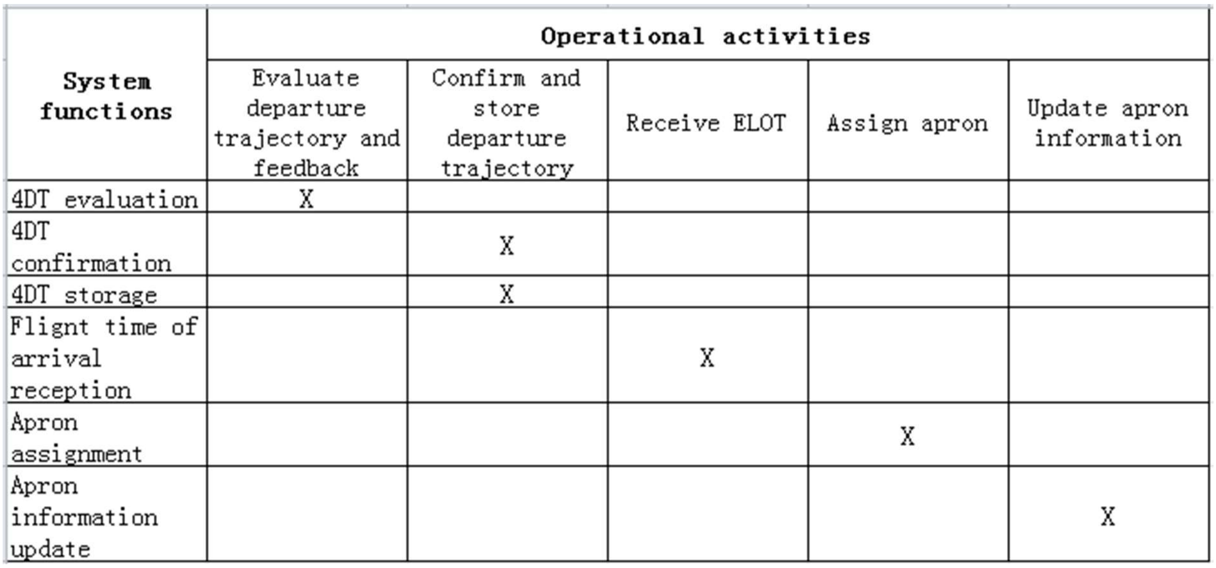


System functions	Operational activities								
	Apply for flight	Submit ideal flight trajectory	Evaluate flow management impact	Submit TOBT	Confirm departure clearance	Generate initial reroute trajectory	Submit initial reroute trajectory	Receive reroute trajectory	Send reroute trajectory
Flight application	X								
4DT planning		X				X			
4DT sending		X					X		X
4DT reception								X	
Flow management impact evaluation			X						
Flignt time of arrival sending				X					
Clearance confirmation					X				

Figure 17 Activity-to-function traceability matrix of the airline node

4.2.1.8 AIRPORT

The activity-to-function traceability matrix of the airport node is shown in Fig. 18.

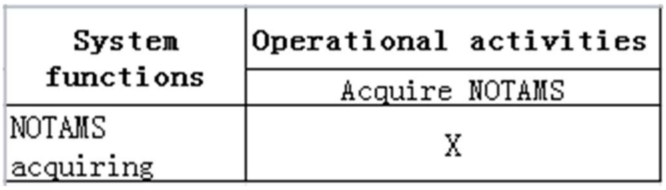


System functions	**Operational activities**				
	Evaluate departure trajectory and feedback	Confirm and store departure trajectory	Receive ELOT	Assign apron	Update apron information
4DT evaluation	X				
4DT confirmation		X			
4DT storage		X			
Flignt time of arrival reception			X		
Apron assignment				X	
Apron information update					X

Figure 18 Activity-to-function traceability matrix of the airport node

4.2.1.9 AVIATION INFORMATION MANAGEMENT

The activity-to-function traceability matrix of the aviation information management is shown in Fig. 19.

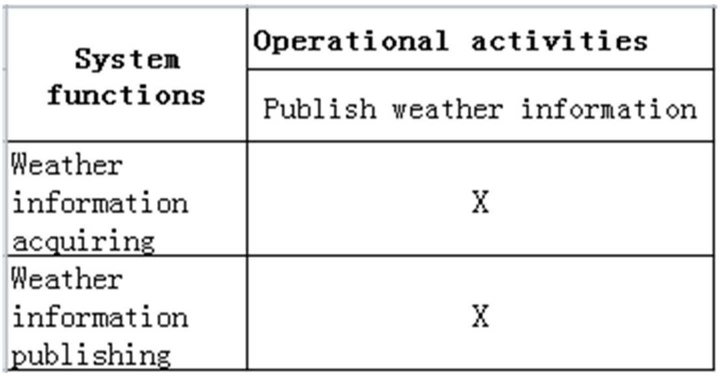


System functions	**Operational activities**
	Acquire NOTAMS
NOTAMS acquiring	X

Figure 19 Activity-to-function traceability matrix of the aviation information management node

4.2.1.10 WEATHER SERVICE DEPARTMENT

The activity-to-function traceability matrix of the weather service department is shown in Fig. 20.



System functions	**Operational activities**
	Publish weather information
Weather information acquiring	X
Weather information publishing	X

Figure 20 Activity-to-function traceability matrix of the weather service department node

4.2.2. CONCLUSIONS

From Fig. 5 to Fig. 20, it can be seen that there is a mapping relationship between the operational activities of each operational node and its system functions. There is no isolated operational activity which is not supported by any system function, and there is no redundant system function. The architecture meets the requirements for activity-to-function traceability.

4.3. VALIDATION OF CONFORMANCE BETWEEN ARCHITECTURE AND OPERATIONAL CONCEPT

The above validation activities can validate the logic correctness, data consistency and activity-to-function traceability within the architecture model, but they can't fully explain that the requirement transition from greener ATM architecture to operational concept is consistent. Therefore, it needs to simulate the architecture model and the greener operational concept scenario in coordination to validate the conformance.

4.3.1. COORDINATED SIMULATION PROCESS OF ARCHITECTURE MODEL AND GREENER OPERATIONAL CONCEPT SCENARIO

The coordinated simulation process of the architecture model based on the joint simulation platform and the greener operational concept scenario is as follows:

- In the data interaction module, load the architecture model built with SysML-based architecture modeling tool and the typical scenario model of green long-route operation built with visualized scenario simulation tool respectively.
- Analyze the architecture model, identify the events that trigger state transition in the operation architecture state machine models and generate an event list.
- Analyze the typical scenario model of greener long-haul operation, and identify the information interaction in the scenario. For each interaction information, a scenario event is created in the data interaction module, and the event type and triggering time are configured.
- In the data interaction module, the state machine trigger event is mapped with the scenario trigger event to establish a data interaction channel. Generate an executable file after successful mapping.
- Activate the architecture modeling tool and the visualized scenario simulation tool at the same time, run the executable file, establish coordinated simulation, and control the start, pause and stop of simulation via the simulation control panel. During the simulation, the visualized scenario simulation tool will fast-simulate the operation scenario based on the timeline. When the event created in the scenario is triggered, the architecture state machine event linked with it will be triggered synchronously, resulting in the state transition of the state machine model of corresponding operational node.
- By examining and analyzing the coordinated simulation process, the consistency between the architecture model and the concept of green operation can be validated.

4.3.2. EXAMPLE OF SIMULATION RESULTS

Fig. 21 provides an example of the simulation process of various event triggers and corresponding state transitions. The left half is the state transition of the node state diagram model of the ATC Operation Management Center, and the right half is the demonstration interface of the greener long-haul operation scenario in the visualized scenario simulation tool. The figure shows that after the airline sends the flight request to the ATC Operation Management Center, the state of the ATC Operation Management Center node changes.

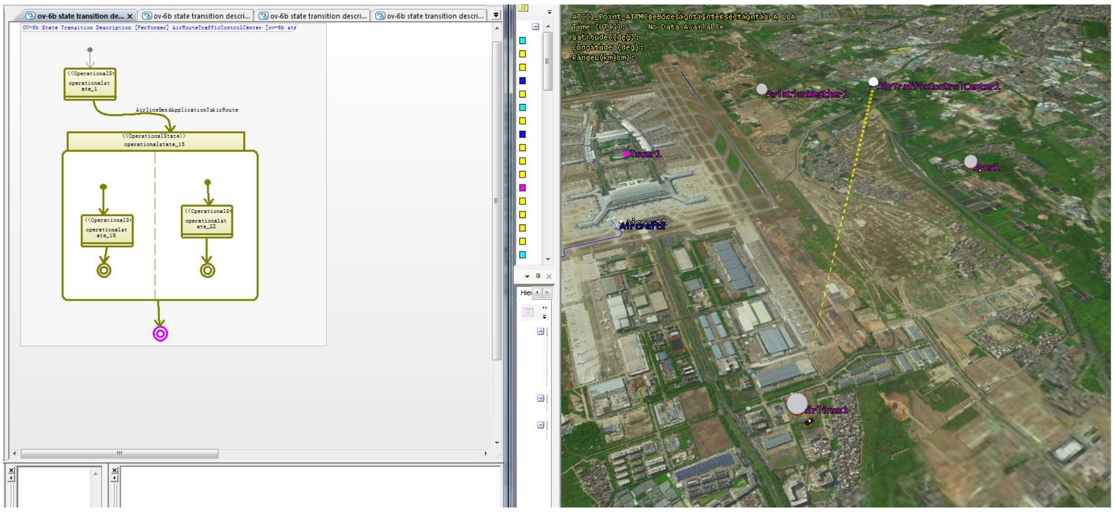


Fig. 21 Coordinated simulation process of architecture models and greener operational concept scenario

4.3.3. DYNAMIC BEHAVIOR ANALYSIS OF OPERATIONAL NODE

Based on the coordinated simulation process between the architecture models and the operation scenario, the dynamic behavior of the operational node can be analyzed, which is to examine the consistency between the state transition and trigger events during the execution of the operational node state machine model and the corresponding events in the operation scenario simulation to verify the conformance of the architectural model to the concept. Table 2 ~ Table 11 show the results for each operational node. The first column lists all the state transitions in the logical sequence. The second column lists the triggering events which trigger the transitions. The third column illustrates the events occurring in the visualized scenario which correspond to the triggering events, with the simulation time in the parentheses.

4.3.3.1 AIRCRAFT

Table 2 Dynamic behavior analysis of aircraft node

State transition	Trigger event	Scenario events
Idle → Calculating the departure trajectory	Receiving the departure trajectory message from the tower	The tower uploads the departure trajectory message to the aircraft （16 March 2022 12:57:00-16 March 2022 12:59:00）
Calculating the departure trajectory → Confirming and update the departure trajectory	Receiving the updated departure trajectory from the tower	The tower uploads the updated departure trajectory to the aircraft, ATFMC, airport, area control center and approach control center (16 March 2022 13:11:00-16 March 2022 13:13:00)
Checking the trajectory and status of the aircraft → Sending the departure trajectory message to the airline	Receiving the departure clearance from the tower	The tower issues the departure clearance to the aircraft (16 March 2022 13:18:00-16 March 2022 13:19:00)
Sending the departure trajectory	Receiving the clearance	The airline feed it back to the

State transition	Trigger event	Scenario events
message to the airline → Confirming the departure clearance with the tower	confirmation from the airline	aircraft after confirming the departure trajectory message (16 March 2022 13:22:00-16 March 2022 13:23:00)
Confirming the departure clearance with the tower → Pushing out	Receiving the push-out clearance from the tower	The tower issues the push-out clearance to the aircraft (16 March 2022 13:26:00-16 March 2022 13:27:00)
Pushing out → Taxiing out to the runway threshold	Receiving the control arrival time from the tower	The tower sends the control arrival time to the aircraft (16 March 2022 13:34:00-16 March 2022 13:35:00)
Waiting at the runway threshold→ Confirming the clearance and entering the runway	Receiving the runway access clearance from the tower.	The tower issues the runway access clearance to the aircraft (16 March 2022 13:39:20-216 March 2022 13:39:50)
Confirming the clearance and entering the runway → Confirming the take-off clearance	Receiving the take-off clearance from the tower	The tower issues the take-off clearance to the aircraft (16 March 2022 13:40:10-16 March 2022 13:40:40)
Confirming the take-off clearance → Taking off	The take-off time arrives	The aircraft starts to take off (16 March 2022 13:41:00)
Taking off → Contacting the approach control centering	Receiving the control handover message from the tower	The tower transfers control to the approach control center (16 March 2022 13:41:20-16 March 2022 13:41:40)
Contacting the approach control centering → Entering the departure flight queue and start climbing	Receiving the confirmation message from the approach control center	The approach control center sends the control handover confirmation message to the aircraft (16 March 2022 13:42:00)
Sending a climb conflict alert to the approach control cent → Perform the conflict resolution	Receiving the conflict resolution instruction from the approach control center	The approach control center issues the resolution instruction {16 March 2022 13:53:00}
Performing the conflict resolution → Confirming the control handover	Receiving the control handover message from the approach control center	The approach control centers hands over the control to the area control center (16 March 2022 13:51:30-16 March 2022 13:52:50)
Confirming the control handover → Start cruising	Reaching the cruise altitude	The aircraft enters the cruise phase after reaching the cruise altitude (16 March 2022 13:53:40)
Identifying the more fuel-efficient flight level → Confirming the clearance of flight level change and changing the flight level.	Receive the clearance to change the flight level from the area control center.	The area control center assesses that the airspace operation situation meets the requirements for flight level change, and issues the change clearance to the aircraft (16 March 2022 13:54:40-16 March 2022 13:54:50)
Confirming the clearance for flight level change and changing the flight level → Confirming the new cruising trajectory and cruising according to the new trajectory.	Receiving the new cruise reference trajectory from the area control center	The area control center updates the ground reference flight trajectory, and issues the updated reference trajectory to the aircraft (16 March 2022 13:56:00-16 March 2022 13:56:10)
Confirming the new cruising	Receiving the meteorological	The area control center sends

State transition	Trigger event	Scenario events
trajectory and cruise according to the new trajectory → Storing the meteorological message and generating the initial rerouting trajectory.	message sent by the area control center	meteorological message to the aircraft (16 March 2022 14:54:00-16 March 2022 14:54:30)
Storing the meteorological message and generating the initial rerouting trajectory → Requesting a rerouting trajectory	Receiving the rerouting trajectory from the airline	The airline receives the rerouting trajectory and feeds it back to the aircraft (16 March 2022 14:58:00-16 March 2022 14:58:10)
Requesting a rerouting trajectory → Recalculating the trajectory	Receive the detour clearance from the area control center	After receiving the request, the area control center issues a detour clearance to the aircraft (16 March 2022 14:58:40-16 March 2022 14:58:50)
Recalculating the trajectory → cruising following the updated reference trajectory	Receiving the updated reference trajectory from the area control center	The area control center updates the ground reference flight trajectory, and issues the updated reference trajectory to the aircraft (16 March 2022 14:59:40-16 March 2022 14:59:50)
Entering the sequencing management area → Developing the initial approach trajectory and transmitting the ETA window.	Receiving the meteorological and operational message from the area control center	The area control center sends meteorological message to the aircraft (16 March 2022 14:54:00-16 March 2022 14:54:30)
Developing the initial approach trajectory and transmit the ETA window → Confirming the CTA and the updated trajectory	Receiving the negotiated CTA uploaded by the area control center	The area control center uploads the negotiated CTA to the aircraft (27 Sep 2021 00:13:00-27 Sep 2021 00:14:00)
Confirming the CTA and the updated trajectory → Confirming the descent clearance	Receiving the descent clearance from the area control center	The area control center issues a descent clearance to the aircraft (27 Sep 2021 00:18:00-27 Sep 2021 00:19:00)
Confirming the descent clearance → Sending the descent conflict alert	The aircraft detects a descent conflict	The aircraft generate a descent conflict alert (27 Sep 2021 00:19:00-27 Sep 2021 00:19:30)
Sending the descent conflict alert → Executing the conflict resolution instruction	Receiving the conflict resolution instruction from the area control center	The area control center issues a conflict resolution instruction to the aircraft (27 Sep 2021 00:19:30-27 Sep 2021 00:20:00)
Executing the conflict resolution instruction → Confirming the control handover	Receiving the control handover message from the area control center	The area control center hand over the control to the approach control center (27 Sep 2021 00:20:00-27 Sep 2021 00:20:30)
Confirming the control handover → Confirming the approach clearance	Receiving the approach clearance from the approach control center	The approach control center issues the approach clearance to the aircraft (27 Sep 2021 00:23:30-27 Sep 2021 00:25:00)
Confirming the approach clearance → Approach according to the safety interval	Receiving the airborne interval hold authorization from the approach control center	The approach control center authorizes airborne interval hold to the aircraft (27 Sep 2021 00:25:00-27 Sep 2021 00:26:00)

State transition	Trigger event	Scenario events
Approaching according to the safe interval → Confirming and update the taxiing path.	Receiving the updated taxi path from the approach control center.	The approach control center uploads the updated taxi path to the aircraft (27 Sep 2021 00:27:00-27 Sep 2021 00:28:00)
Confirming and update the taxiing path → Preparing for landing.	Receiving the runway meteorological message from the approach control center	The approach control center informs the aircraft of the runway meteorological message (27 Sep 2021 00:29:00-27 Sep 2021 00:30:00)
Preparing for landing → Confirming the updated runway message and requesting the landing clearance	Receiving the updated runway message from the tower	The airport reallocates the runway (27 Sep 2021 00:31:00-27 Sep 2021 00:32:00)
Confirming the updated runway message and requesting the landing clearance → Confirming the landing clearance and perform the landing	Receiving the landing clearance from the tower	The tower control center issues the landing clearance to the aircraft (27 Sep 2021 00:33:00-27 Sep 2021 00:34:00)
Confirming the landing clearance and perform the landing → Taxiing off the runway	The aircraft arrives at the runway threshold	The aircraft arrives at the runway threshold (27 Sep 2021 00:36:00)
Taxiing off the runway → Confirming the taxiing-in clearance	Receiving the taxi-in clearance from the tower	The tower control center issues the taxi-in clearance to the aircraft (27 Sep 2021 00:40:00-27 Sep 2021 00:41:00)
Confirming the taxiing-in clearance → Confirming the parking clearance	Receiving the parking clearance from the tower	The tower control center issues the parking clearance to the aircraft (27 Sep 2021 01:00:00-27 Sep 2021 01:02:00)

4.3.3.2 AREA CONTROL CENTER

Table 3 Dynamic behavior analysis of area control center node

State transition	Trigger event	Scenario events
Idle → Assessing the departure trajectory	Receiving the negotiated departure trajectory message from the tower	The tower sends the departure trajectory Receiving to ATFMC, airport, area control center and approach control center (16 March 2022 13:04:00-16 March 2022 13:06:00)
Assessing the departure trajectory → Confirming and store the departure trajectory	Receiving the departure trajectory updated and issued by the tower	The tower uploads the updated departure trajectory to the aircraft, ATFMC, airport, area control center and approach control center (16 March 2022 13:11:00-16 March 2022 13:13:00)
Confirming and store the departure trajectory → Confirming the control handover	Receiving the control handover request from the approach control center	The tower transfers control to the approach control center (16 March 2022 13:41:20-16 March 2022 13:41:40)
Monitoring the cruise operation	Receiving the request to change to	The aircraft requests to change the

State transition	Trigger event	Scenario events
→ Assessing the airspace situation	a more fuel-efficient flight level from the aircraft	flight level (16 March 2022 13:54:10-16 March 2022 13:54:20)
Evaluating the airspace situation → Issuing the clearance for flight level change.	The assessment results meet the requirements of flight level change.	The area control center assesses that the airspace operation situation meets the flight level change (16 March 2022 13:54:30)
Issuing the flight level change clearance → Updating and issuing a new cruise reference trajectory.	Receiving the EPP data from the aircraft	The aircraft transmits the latest EPP data to the area control center after the aircraft completes the flight level change (16 March 2022 13:55:30-16 March 2022 13:55:40)
Updating the new cruise reference trajectory → Sending the meteorological message.	Receiving the meteorological message from the weather service department	The area control center sends meteorological message to the aircraft (16 March 2022 14:54:00-16 March 2022 14:54:30)
Sending the meteorological message → Confirming the rerouting trajectory	Receiving the rerouting trajectory from ATFMC	ATFMC sends the confirmed rerouting trajectory to the area control center and the airline (16 March 2022 14:57:40-16 March 2022 14:57:50)
Confirming the rerouting trajectory → Issuing the detour clearance	Receiving the detour clearance request from the aircraft	The aircraft receives the rerouting trajectory, and applies to the area control center for a detour clearance (16 March 2022 14:58:20-16 March 2022 14:58:30)
Issuing the detour clearance → Updating the reference trajectory	Receiving the EPP data from the aircraft	After receives the detour clearance, the aircraft recalculating the trajectory and transmit the EPP data (16 March 2022 14:59:00-16 March 2022 14:59:10)
Planning the approach trajectory → Negotiating the CTA	Receiving the ETA window from the aircraft	The aircraft transmits the ETA window to the approach control center (27 Sep 2021 00:12:00-27 Sep 2021 00:12:30)
Negotiating the CTA → Uploading the CTA	Receiving the CTA feedback from the approach control center, tower and ATFMC	The approach control center, tower, ATFMC negotiate CTA with the area control center (27 Sep 2021 00:12:30-27 Sep 2021 00:13:30)
Uploading the CTA→ Updating and share the approach trajectory	Receiving the trajectory confirmation from the aircraft	The aircraft confirms and updates the trajectory (27 Sep 2021 00:14:00-27 Sep 2021 00:14:30)
Updating and share the approach trajectory → Uploading the taxi path.	Receiving taxi path from the tower.	The approach control center obtains the updated approach taxi path from the tower (27 Sep 2021 00:17:00-27 Sep 2021 00:17:30)
Uploading the taxi path → Issuing a descent clearance.	The aircraft arrives at TOD	The aircraft arrives at TOD (27 Sep 2021 00:18:00)
Issuing the descent clearance →	Receiving the conflict alert from	The aircraft generate a descent

State transition	Trigger event	Scenario events
Issuing conflict resolution instruction	the aircraft	conflict alert (27 Sep 2021 00:19:00-27 Sep 2021 12:20:00 AM)
Issuing the conflict resolution instruction → Transferring the control to the approach control center	The aircraft is about to enter the terminal area	The aircraft is about to enter the terminal area (27 Sep 2021 00:20:00)

4.3.3.3 APPROACH CONTROL CENTER

Table 4 Dynamic behavior analysis of the approach control center node

State transition	Trigger event	Scenario events
Idle → Assessing the departure trajectory	Receiving the negotiated departure trajectory message from the tower	The tower sends the departure trajectory Receiving to ATFMC, airport, area control center and approach control center (16 March 2022 13:04:00-16 March 2022 13:06:00)
Assessing the departure trajectory → Confirming and store the departure trajectory	Receiving the departure trajectory updated and issued by the tower	The tower uploads the updated departure trajectory to the aircraft, ATFMC, airport, area control center and approach control center (16 March 2022 13:11:00-16 March 2022 13:13:00)
Confirming and store the departure trajectory → Confirming the control handover	Receiving the control handover request from the tower	The tower transfers control to the approach control center (16 March 2022 13:41:20-16 March 2022 13:41:40)
Confirming the control handover → Monitoring the climbing operation	Receiving the contact from the aircraft	The aircraft confirms the handover of control, join the departure flight queue, and then start climbing (16 March 2022 13:42:00)
Monitoring the climb operation → Conflict resolution	Receiving the climb conflict alert from the aircraft	The aircraft sends the conflict alert to the approach control center (16 March 2022 13:49:00-16 March 2022 13:50:00)
Conflict resolution→ Send the updated climbing reference trajectory	Complete the reference trajectory update	The approach control center updates the reference trajectory (16 March 2022 13:53:30)
Issue the updated climbing reference trajectory → Handover the control to the area control center	The aircraft reaches the cruise altitude	The aircraft enters the cruise phase after reaching the cruise altitude (16 March 2022 13:53:40)
Idle → Negotiate the CTA	Receiving the CTA negotiation request from the area control center	The approach control center, tower, ATFMC negotiate CTA with the area control center (27 Sep 2021 00:12:30-27 Sep 2021 00:13:30)
Negotiate the CTA→ Confirming and store the updated approach trajectory	Receiving the updated approach trajectory from the area control center	The area control center updates and shares the approach trajectory with the approach control center, tower and ATFMC (27 Sep 2021

State transition	Trigger event	Scenario events
		00:14:00-27 Sep 2021 00:15:30)
Confirming and store the updated approach trajectory → Confirming the control handover	Receiving the control handover request from the area control center	The area control center transfers the control to the approach control center (27 Sep 2021 00:20:00-27 Sep 2021 00:20:30)
Confirming the control handover → Issue the approach clearance and authorize the interval hold	The aircraft is about to arrive at IAF	The aircraft is about to arrive at IAF (27 Sep 2021 00:23:00)
Issue the approach clearance and authorize the interval hold → Handover the control to the tower	The aircraft is about to arrive at FAF	The aircraft is about to arrive at FAF (27 Sep 2021 00:30:00)

4.3.3.4 TOWER CONTROL CENTER

Table 5 Dynamic behavior analysis of the tower control center node

State transition	Trigger event	Scenario events
Idle → Storing the planned trajectory	Receiving the planned trajectory updated and issued by ATFMC	The ATFMC updates and issues the planned trajectory, and sends it to the airlines, the weather service department and the tower control center (16 March 2022 12:44:00-16 March 2022 12:46:00).
Storing the planned trajectory → Storing the meteorological message	Receiving the meteorological message issued by the weather service department	The weather service department issues the meteorological message to the tower (16 March 2022 12:47:00-16 March 2022 12:49:00)
Storing the meteorological message → Sending NOTAMS	Receiving the NOTAMS request from the aviation information management	The weather service department sends NOTAMS to the tower (16 March 2022 12:50:00-16 March 2022 12:52:00)
Sending NOTAMS→ Assigning the taxi path	Receiving the TOBT submitted by the airline	The airline submits the TOBT to the tower (16 March 2022 12:53:00-16 March 2022 12:55:00)
Assigning the taxi path → Negotiating and updating the departure trajectory.	Receiving the departure trajectory from the aircraft	The tower uploads the departure trajectory message to the aircraft (16 March 2022 12:57:00-16 March 2022 12:59:00)
Negotiating and updating the departure trajectory → Updating and uploading the departure trajectory	Receiving the departure trajectory assessment feedback from ATFMC, airport, area control center and tower control center	ATFMC, airport, area control center and approach control center jointly participate in negotiation and then feed back to the tower (16 March 2022 13:07:00-16 March 2022 13:09:00)
Updating and uploading the departure trajectory → Issuing the departure clearance	Receiving the departure clearance request from the aircraft	The aircraft sends the departure clearance request to the tower (16 March 2022 13:16:00-16 March 2022 13:17:00)
Issuing the departure	Receiving the push-out clearance	The aircraft sends the push-out

State transition	Trigger event	Scenario events
clearance→ Issuing the push-out clearance	request from the aircraft	clearance request to the tower (16 March 2022 13:24:00-16 March 2022 13:25:00)
Issuing the push-out clearance → Storing the balance message of volume and flow.	Receiving the capacity-demand balance message from ATFMC	ATFMC calculatings the capacity-demand balance message and sends it to the tower (16 March 2022 13:34:00-16 March 2022 13:35:00)
Storing the capacity-demand balance message → Issuing the runway access clearance	The aircraft arrives at the runway threshold	The aircraft arrives at the runway threshold (16 March 2022 13:39:00)
Issuing the runway access clearance → Issuing the take-off clearance	The aircraft enters the runway	The aircraft confirms the clearance and enter the runway (16 March 2022 13:40:00)
Issuing the take-off clearance → Transferring the control to the approach control center	The aircraft begins to take off	The aircraft starts to take off (16 March 2022 13:41:00)
Idle → Negotiating the CTA	Receiving the CTA negotiation request from the area control center	The approach control center, tower, ATFMC negotiate CTA with the area control center (27 Sep 2021 00:12:30-27 Sep 2021 00:13:30)
Negotiating the CTA→ Confirming and storing the updating approach trajectory	Receiving the updated approach trajectory from the area control center	The area control center updates and shares the approach trajectory with the approach control center, tower and ATFMC (27 Sep 2021 00:14:00-27 Sep 2021 00:15:30)
Confirming and storing the updating approach trajectory → Save the updating parking sapce message	Receiving the updated parking space message from the airport	The airport sends the allocated parking space message to the tower (27 Sep 2021 00:16:00-27 Sep 2021 00:17:30)
Save the updating parking place message → Confirming the control transferring	Receiving the control handover request from the approach control center	The area control center hand over the control to the approach control center (27 Sep 2021 00:20:00-27 Sep 2021 00:20:30)
Confirming the control transferring → Uploading runway reallocation message	Receiving the runway reallocation message from the airport	The airport reallocates the runway (27 Sep 2021 00:31:00-27 Sep 2021 00:32:00)
Uploading the runway reassignment message → Issuing the landing clearance	Receiving the landing clearance request from the aircraft	The aircraft issues the landing clearance request to the tower (27 Sep 2021 00:32:00-27 Sep 2021 00:33:00)
Issuing the landing clearance → Issuing the taxi-in clearance	The aircraft arrives at the runway threshold	The aircraft arrives at the runway threshold (27 Sep 2021 00:36:00)
Issuing the taxi-in clearance → Issuing the parking clearance	The aircraft arrives at the taxiway threshold	The aircraft arrives at the taxiway threshold (27 Sep 2021 01:00:00)

4.3.3.5 AIR TRAFFIC FLOW MONITORINGING CENTER

Table 6 Dynamic behavior analysis of air traffic flow monitoringing center node

State transition	Trigger event	Scenario events
Idle → Developing flow management strategy	Receiving the airspace status and use restrictions message issued by ARTCC	ARTCC issues the airspace status and use restrictions to the airline and ATFMC (16 March 2022 12:34:00-16 March 2022 12:36:00)
Developing flow management strategy → Issuing the planned trajectory	Receiving the feedback message from the airline	The airline confirm the traffic control policy with ATFMC upon its assessment (16 March 2022 12:37:00-16 March 2022 12:39:00.000)
Issuing the planned trajectory → Assessing the departure trajectory	Receiving the negotiated departure trajectory message from the tower	The tower sends the departure trajectory Receiving to ATFMC, airport, area control center and approach control center (16 March 2022 13:04:00-16 March 2022 13:06:00)
Assessing the departure trajectory → Confirming and store the departure trajectory	Receiving the departure trajectory updated and issued by the tower	The tower issues the updated departure trajectory to the aircraft, ATFMC, airport, area control center and approach control center (16 March 2022 13:11:00-16 March 2022 13:13:00)
Predicting and monitoring the capacity-demand balance in the terminal area → Assessing the capacity-demand balance message	Receiving the capacity-demand balance message request from the tower	The tower requests the capacity-demand balance message from ATFMC (16 March 2022 13:32:00-16 March 2022 13:33:00)
Assessing the capacity-demand balance message → Assessing and update the trajectory	Receiving the updated climb reference trajectory from the approach control center	The approach control center sends the updated reference trajectory to the aircraft, area control center and ATFMC (16 March 2022 13:51:00-16 March 2022 13:51:20)
Monitoring the air traffic flow → Confirming the new cruise trajectory	Receiving the new cruise reference trajectory from the area control center	The area control center issues the updated reference trajectory to the aircraft and ATFMC (16 March 2022 13:56:00-16 March 2022 13:56:10)
Confirming the new cruise trajectory→ Assessing the rerouting trajectory and sending the confirmed rerouting trajectory	Receiving the initial rerouting trajectory from the airline	The airline submits the initial rerouting trajectory to ATFMC (16 March 2022 14:56:10-16 March 2022 14:57:30)
Assessing the rerouting trajectory and sending the confirmed rerouting trajectory → Monitoring the air traffic flow	Receiving the updated reference trajectory from the area control center	The area control center issues the updated reference trajectory to the aircraft and ATFMC (16 March 2022 14:59:40 PM-16 March 2022 2:59:50 PM)
Monitoring the air traffic flow → Negotiating the CTA	Receiving the CTA negotiation request from the area control center	The approach control center, tower, ATFMC negotiate CTA with the area control center (27 Sep 2021 00:12:30-27 Sep 2021 00:13:30)
Negotiating the CTA→	Receiving the updated approach	The area control center updates

State transition	Trigger event	Scenario events
Generating and share the ELDT	trajectory from the area control center	and shares the approach trajectory with the approach control center, tower and ATFMC (27 Sep 2021 00:14:00-27 Sep 2021 00:15:30)
Generating and share the ELDT→ Confirming the updated descent reference trajectory	Receiving the updated descent reference trajectory from the area control center	The area control center updates the descent reference trajectory, and the approach control center and ATFMC participate in the assessment, update and confirmation (27 Sep 2021 00:19:30-27 Sep 2021 00:20:00)

4.3.3.6 ATC OPERATION MANAGEMENT CENTER

Table. 7 Dynamic behavior analysis of ATC Operation Management Center node

State transition	Trigger event	Scenario events
Idle → Issuing the airspace status and use restrictions message	Receiving the flight request from the airline	The airline requests flight from ARTCC (16 March 2022 12:31:00-16 March 2022 12:33:00)

4.3.3.7 AIRLINE

Table 8 Dynamic behavior analysis of airline node

State transition	Trigger event	Scenario events
Flight requesting → Developing and submitting the ideal flight path	Receiving the airspace status and use restrictions message issued by ARTCC	ARTCC issues the airspace status and use restrictions to the airline and ATFMC (16 March 2022 12:34:00-16 March 2022 12:36:00)
Developing and submitting the ideal flight path → evaluating the impact of traffic flow control strategy	Receive a flow control policy from ATFMC.	ATFMC sends the traffic flow management strategy to the airline (16 March 2022 12:37:00-16 March 2022 12:39:00)
Evaluating the impact of traffic flow control strategy → Submitting TOBT	Receiving the planned trajectory updated and issued by ATFMC	The ATFMC updates and issues the planned trajectory, and sends it to the airlines, the weather service department and the tower control center (16 March 2022 12:44:00-16 March 2022 12:46:00).
Submitting TOBT→ Confirming the departure clearance	Receiving the departure message from the aircraft	The aircraft sends the departure message to the airline (16 March 2022 13:20:00-16 March 2022 13:21:00)
Confirming the departure clearance → Confirming and sending the initial rerouting trajectory	Receiving the initial rerouting trajectory from the aircraft	The aircraft generates the initial rerouting trajectory and send it to the airline (16 March 2022 14:54:40-16 March 2022 14:56:00)
Confirming and sending the initial rerouting trajectory → Confirming the new rerouting trajectory	Receiving the rerouting trajectory confirmed by ATFMC	ATFMC sends the confirmed rerouting trajectory to the area control center and the airline (16 March 2022 14:57:40-16 March

State transition	Trigger event	Scenario events
		2022 14:57:50)

4.3.3.8 AIRPORT

Table 9 Dynamic behavior analysis of airport node

State transition	Trigger event	Scenario events
Idle → Assessing the departure trajectory	Receiving the negotiated departure trajectory message from the tower	The tower sends the departure trajectory Receiving to ATFMC, airport, area control center and approach control center (16 March 2022 13:04:00-16 March 2022 13:06:00)
Assessing the departure trajectory → Confirming and storing the departure trajectory	Receiving the departure trajectory updated and issued by the tower	The tower uploads the updated departure trajectory to the aircraft, ATFMC, airport, area control center and approach control center (16 March 2022 13:11:00-16 March 2022 13:13:00)
Idle→ Allocating the parking space	Receiving ELDT from ATFMC	ATFMC shares the ELDT time with the airport (27 Sep 2021 00:15:30-27 Sep 2021 00:16:00)

4.3.3.9 AVIATION INFORMATION MANAGEMENT

Table 10 Dynamic behavior analysis of aviation information management

State transition	Trigger event	Scenario events
Idle → Storing the planned trajectory	Receiving the planned trajectory updated and issued by ATFMC	The ATFMC updates and issues the planned trajectory, and sends it to the airlines, the weather service department and the tower control center (16 March 2022 12:44:00-16 March 2022 12:46:00).

4.3.3.10 WEATHER SERVICE DEPARTMENT

Table 11 Dynamic behavior analysis of weather service department

State transition	Trigger event	Scenario events
Idle → Storing the planned trajectory	Receiving the planned trajectory updated and issued by ATFMC	The ATFMC updates and issues the planned trajectory, and sends it to the airlines, the weather service department and the tower control center (16 March 2022 12:44:00-16 March 2022 12:46:00).
Storing the planned trajectory → Issuing the meteorological message.	Receiving the meteorological message request from the area control center	The area control center requests meteorological message from the weather service department (16 March 2022 14:49:00-16 March 2022 14:50:00)

4.3.4. DYNAMIC SEQUENCE DIAGRAM

During the execution of the state diagram model, the dynamic sequence diagrams of all operational nodes will be automatically generated, which reflects the system sequencing operation logic consistency with the actual operation of the model, including operational activities and information interaction. Due to the limited space, this document only captures part of the dynamic sequence diagram of departure phase (Fig. 22), indicating the process of departure clearance issuance and confirmation involving nodes such as aircraft, airline and tower control center.

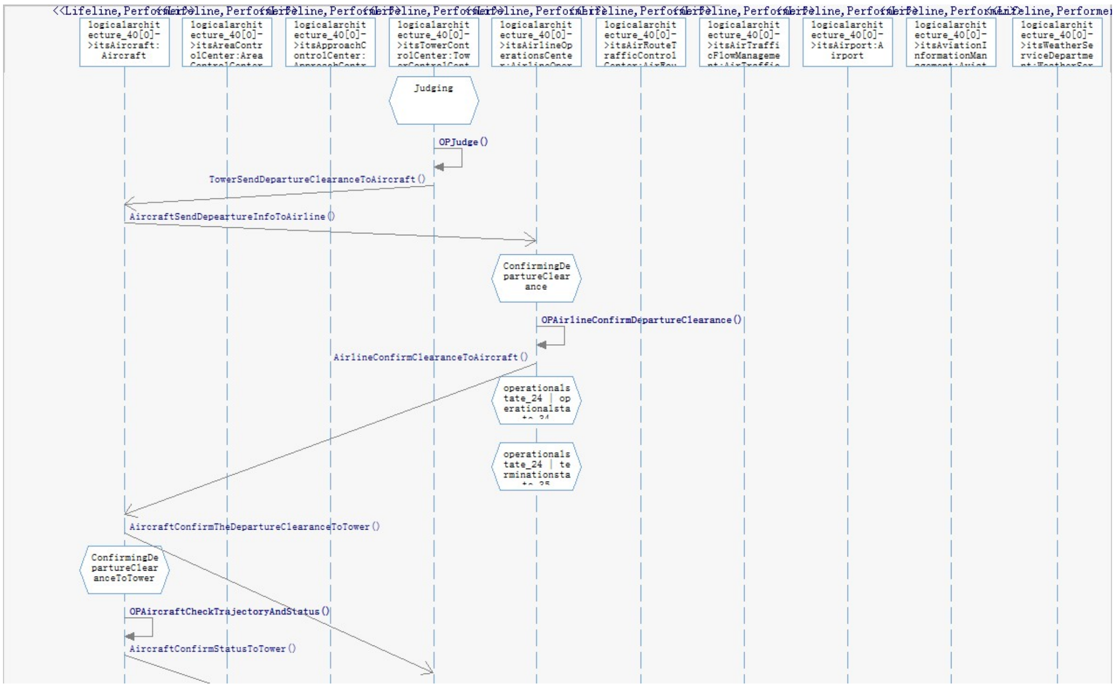


Fig. 22 Example of dynamic sequence diagram of departure phase

The dynamic sequence diagram of the whole operation process is generated in the validation. By comparing it with the detailed operation process of the simulation scenario and the static sequence diagram based on the simulation scenario, no obvious logical contradiction and deficiency are found, thus proves to have good behavior consistency.

4.3.5. CONCLUSIONS

By examining the coordinated simulation process between the architecture model and the green operation scenario, it can be inferred that the state transition during the execution process of the architecture model is basically consistent with the behavior logic of each node in the operation scenario over time. The models can accurately reflect the concept of greener long-haul operation and meet the initial objectives of greener ATM architecture development.

5. SUMMARY

The 4DT-based greener air traffic management system incorporating new procedures to reduce fuel consumption and carbon emission is a typical complex system. The architecture analysis of such a system requires methodology and tools from Model-based System Engineering perspective. In WP2.1, greener ATM concepts for long-haul and short-haul flights have been studied. Taking the proposed concepts as the input, greener ATM operational architecture and system architecture have been developed in WP2.2 following an MBSE approach by building SysML-based models describing operation activities and system functions.

Based on the above work, this report demonstrates the process and the results of validation of greener ATM architectures which is the goal of WP2.3. Three validation objectives are identified: data consistency of the models, traceability between operational activities and system functions, and the conformance of the architecture to greener concepts. A joint simulation environment is developed to support the validation activities, composed by SysML-based modeling tool, visualized scenario simulation tool and data exchange module. The validation results show that all objectives are well-achieved.

In conclusion, this report focuses on the qualitative validation and evaluation of architectures with executable models developed in WP2.2 in a system engineering view. Moreover, the proposed validation process in which executable models and visualized scenarios are simulated jointly is also useful to validate the operational performance of ATM concepts like safety, efficiency and environmental impact. To realize this, future work beyond this report is required. For example, attributes with quantitative data such as flight time, speed, distance, fuel consumption, ATCO workload need to be integrated into both the architecture models and scenario models so that more meaningful results can be obtained through simulation for analysis.

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