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GREENER ATM SYSTEM ARCHITECTURE RESEARCH BASED ON COMPLEX SYSTEM ENGINEERING METHOD

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Abstract

Greener aviation has gradually become a development trend of global air transportation industry, which is crucial for achieving sustainable development goals. The realization of greener aviation urgently requires innovation at the level of air traffic operation. Traditional air traffic management is mainly based on the premise of ensuring the safety of aircraft operations, with the goal of maximizing the utilization of airport and airspace service capabilities, paying less attention to the environmental impact induced by air traffic management strategy implementation. The future greener ATM system will focus on energy conservation and emission reduction. Through the implementation of new concepts, technologies and methods such as advanced surface management, continuous climb/descend operation, and collaborative decision-making, the airspace structure, flight trajectory and procedures will be optimized to realize the development requirements of greener aviation.

The research on greener ATM system architecture is necessary to identify the characteristics of greener air traffic operation and to clarify the stakeholder requirements and system capability requirements for greener ATM system. It is also a prerequisite for the research of key technologies for greener ATM and avionic systems. As a typical complex system, the greener ATM system has the following characteristics: 1) multi-business and multi-node, involving the mutual cooperation and information exchange among multiple subsystems such as aircraft, satellites, and ground stakeholders; 2) each subsystem can play its own role and operate independently of other systems; 3) dynamic system which includes a large number of emergent behaviors; 4) central-radiation or distributed network topology which defines the connection among various nodes. Therefore, the analysis of this system requires the selection of appropriate system engineering methods, frameworks, and modeling processes to clearly and accurately reflect system functions and behaviors.

The traditional architecture design approach is a document-centric system engineering method. This method extracts information from multifarious documents, causing divergence in understanding of different designers, and it requires too many iterative processes, which is difficult for information tracking and management. The model-based system engineering (MBSE) method avoids the vagueness and ambiguity caused by document via using the object-oriented, graphical and visualized system modeling language to describe the system, and has good consistency, verifiability and traceability.

This paper proposes a greener ATM system architecture design and development process based on MBSE method. According to analysis of new concepts of air traffic operations for green aviation, areas of change and enhancement beyond existing air traffic operations are identified. Typical greener operation scenarios that implement the above concepts are constructed for long-haul and short-haul operations, and new requirements proposed by various stakeholders under these scenarios are analyzed. Based on the operation scenarios and requirements, the procedures of each flight phase and the information exchange pattern among the operational nodes are identified from the operation perspective, to establish the operational view models. The system composition and system functions of the greener ATM system are defined from the system perspective, and the mapping relationship between system functions and operational activities is created, to establish the system view models. These models include high-level operational concept diagrams, sequence diagrams, state-machine diagrams, etc. Through the development of these architecture models, the requirements of the ATM system supporting greener aviation operational concepts are clearly defined, which provides guidance for the subsequent research of key technologies.

Compared with the traditional method, the MBSE-based greener air traffic management system development process has the following advantages: 1) the model decomposition process helps to explore more details in the system; 2) the model-based architecture analysis can guarantee the consistency in different views; 3) architecture analysis can predict and analyze the emergent behaviors of the system.

Keywords: Greener aviation, Model-based system engineering, ATM system architecture

1. Introduction

The environmental impact of civil air transportation is becoming a focusing problem in many developed countries. The continuously increasing fuel consumption, carbon emission and noise pollution bring challenges to global environment protection, and severely constrain the development of civil air transportation. The impact is significant especially in high-traffic airport terminal airspace with frequent departures and arrivals. According to the ICAO Environmental Report 2016, The CO2 emission of commercial aviation accounts for approximately 2.6% of annual global CO2 emissions. The increased flight delay led by inefficient air traffic operation and less economic flight paths are crucial reasons of excessive fuel consumption and gas emission. Therefore, developed countries and regions like US and Europe are step by step realizing strategic objectives of cleaner and greener aviation in their next generation ATM operational concepts, such as SESAR and NextGen. The 4-dimensional-trajectory-based operation is the core concept of greener air traffic management. 4D trajectory is the precise description of flight paths in the form of space and time (aircraft longitude, latitude and altitude as well as time coordinate), with combination of airspace data, meteorological data, aircraft performance data, flight plans and the estimation of controller intension to predict the future aircraft trajectories. In order to realize greener aviation, the requirements of 4DT-based operation includes more economic and environmental-friendly trajectory optimization, trajectory-based surface operation and optimized departure/arrival procedures, aiming at reducing ground holding time, flight delays and fuel burns.

The ATM system based on 4D trajectory technology is a typical complex system, which possesses the following characteristics: 1) multi-agent, multi-business and multi-node system, involving coordination and information exchange among sub-systems like aircraft, satellites and ground stakeholders; 2) each sub-system can operate independently of other systems; 3) it is a dynamic system involving plenty of evolutionary and emergent behaviors; 4) there is a central-radiant or distributed network structure among operational nodes, which defines their interaction; 5) the effective study on ATM system requires knowledge across different areas such as engineering, economy, policy and business. Therefore, complex system engineering methodology is needed to analyze and research the ATM system. Since the traditional document-based system engineering method extract information from massive documents, there can be divergent understandings among different designers and too many iteration processes are required, which makes information difficult to track and manage. On the contrary, model-based system engineering starts from requirement analysis, realizing consistent, traceable and verifiable system development process using continuous evolution of models instead of documents. By describing systems using object-oriented, graphic and visualized system modeling language, the fuzziness and ambiguity led by documents can be avoided, while system functions and behaviors can be reflected clearly and precisely. As the MBSE method has advantages like high communication efficiency, convenient data accessibility, good traceability and verifiability, MBSE has become a hotspot of aeronautic and astronautic system research and application in recent years.

This paper conducts forward design of greener air traffic operation and system architecture based on model-based complex system engineering methods. Starting from greener air traffic operational concept, typical operational scenario is established, top-level operational requirements are captured, stakeholders and information exchanges among them are identified. A series of greener ATM system architecture models are built from operation and system orientation, and are simulated and validated using visualized simulation tools. The process finally extracts structural detailed ATM system operational requirement list.

2. Greener Air Traffic Operational Concept

The realizing of greener air traffic operation is the result of coordination of multiple stakeholders such as aircraft, ATC, airports and airlines. This paper mainly considers the whole gate-to-gate flight period of a single flight from several hours before departure to arriving at the destination airport, including 9 flight phases: flight planning, taxiing out, taking off, climb, cruising, descend, approach, landing roll and taxiing in. 4D trajectory is the key element throughout each phase.

In order to reduce the unnecessary fuel burn of traditional flight profile, the 4D trajectory requires optimization based on aircraft type, airspace flow condition, weather condition and airline flight intension at flight planning phase. Trajectories of different flights have to be coordinated to avoid potential conflicts.

At surface operation phases the A-CDM mechanism is implemented. By establishing information sharing platform involving ATC, airports and airlines, and integrating flight departure/arrival management system, weather forecasting system and airport operation monitoring system, it is possible to ensure all stakeholders' awareness of flight information, maximum use of airspace/ground resources and reduced flight delays. Furthermore, the trajectory-based surface operation concept is introduced. The time of pushback, taxiing and taking off of each flight is strictly sequenced according to the planned trajectories, addressing the uncertainty at surface taxiing phase, so as to reduce the ground holding time with the engine idling.

At climbing phase, the flight profile of aircraft is based on Continuous Climb Operation (CCO). The aircraft begins cruising at the target flight level planned by airline when entering the appropriate altitude. The flight management system adjusts flight speed based on required time of arrival (RTA) function to meet the time constraint at the merging point in arrival airport terminal area. When capacity/flow imbalance in terminal area is detected, the estimated time of arrival will be postponed so that the delays will be absorbed at cruise phase and the air holding before approach is avoided. When rerouting strategy is needed because of flight conflicts and severe weather, the aircraft will negotiate with ground ATCs. Aircraft with related airborne capabilities will choose the optimized rerouting path on their own, while other aircraft will be assisted by ground ATM system to decide rerouting strategy.

When entering terminal areas the aircraft will take Continuous Descent Operation (CDO) approach procedures which are more economic and effectively reduce descent time, realizing less fuel burn and noise impact. The taxiing after landing will also rely on optimized 4D trajectory to ensure efficient and environmental-friendly surface operation.

3. Greener Air Traffic Operation Architecture Development

The development process of greener air traffic operation architecture based on MBSE methods is shown in Figure 1. First the greener air traffic top-level requirements and operational requirements of stakeholders are captured from the greener air traffic operational concept, and typical operational scenario is designed according to ConOps and real conditions. Operational and system architectures are built from operation and system orientation, respectively. Visual scenario demonstration is conducted using simulation tools and jointly validated with the generated models. Finally the structural requirements of ATM system capabilities are extracted, and delivered to users for verification. The verified requirements are provided to ATM OEMs for future system device development.

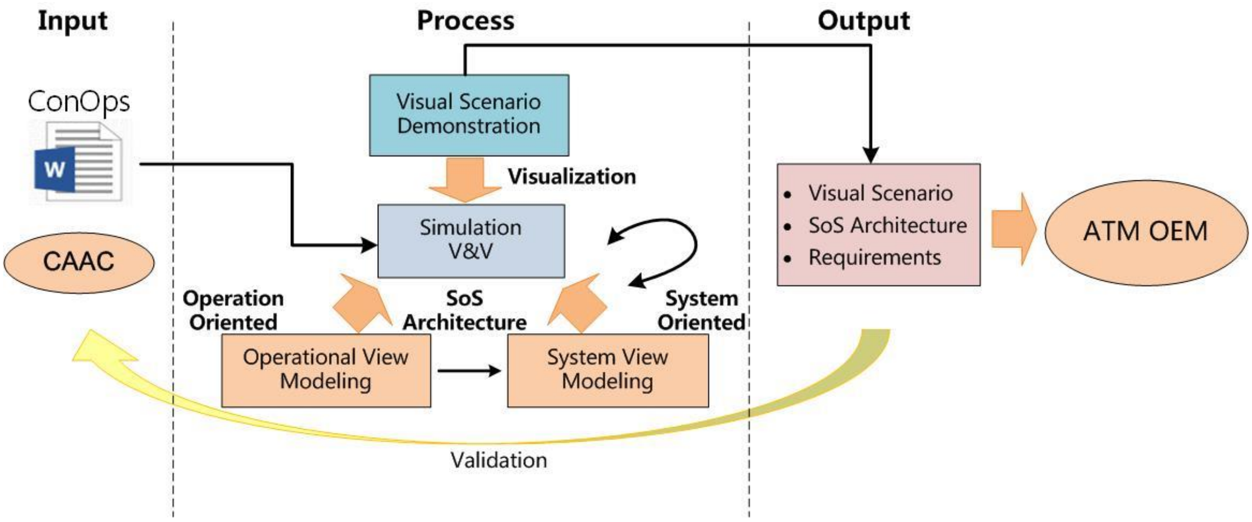

Figure 1 – MBSE-based greener air traffic operation architecture development process

3.1 Operational View Modeling

Operational View is the description of operation objectives and the required elements, activities and information exchanges to realize them, including textual and graphic models. It also defines the type and frequency of the exchanged information, and what kind of operations and activities can be supported. Operational View models consist of high-level operational concept diagram, operational node connectivity description, operational activity model, operational event trace description and operational state transition description.

3.1.1 High-level Operational Concept Diagram

High-level operational concept diagram describes the system environment and the interaction between system architecture and external systems, which can be expressed in images, graphic texts and videos, etc. This model emphasizes involved stakeholders in ATM operation, and provides scenario-based operational architecture organization method.

In order to establish this model, the typical scenario of 4DT-based greener air traffic operation should be identified (shown as Figure 2). This paper chooses the whole flight process of a single civil flight from Beijing Capital Airport to Shanghai Pudong Airport as the scenario of interest. This scenario covers related activities and information exchange among operational nodes including the chosen aircraft, other aircraft, ATC, airports and airlines. In addition, we assume an emergent event that the flight encounters severe weather at cruising phase. The aircraft executes optimized rerouting strategy after coordination with area control centers, and carries out conflict resolution with other aircraft via Airborne Collision Avoidance System.

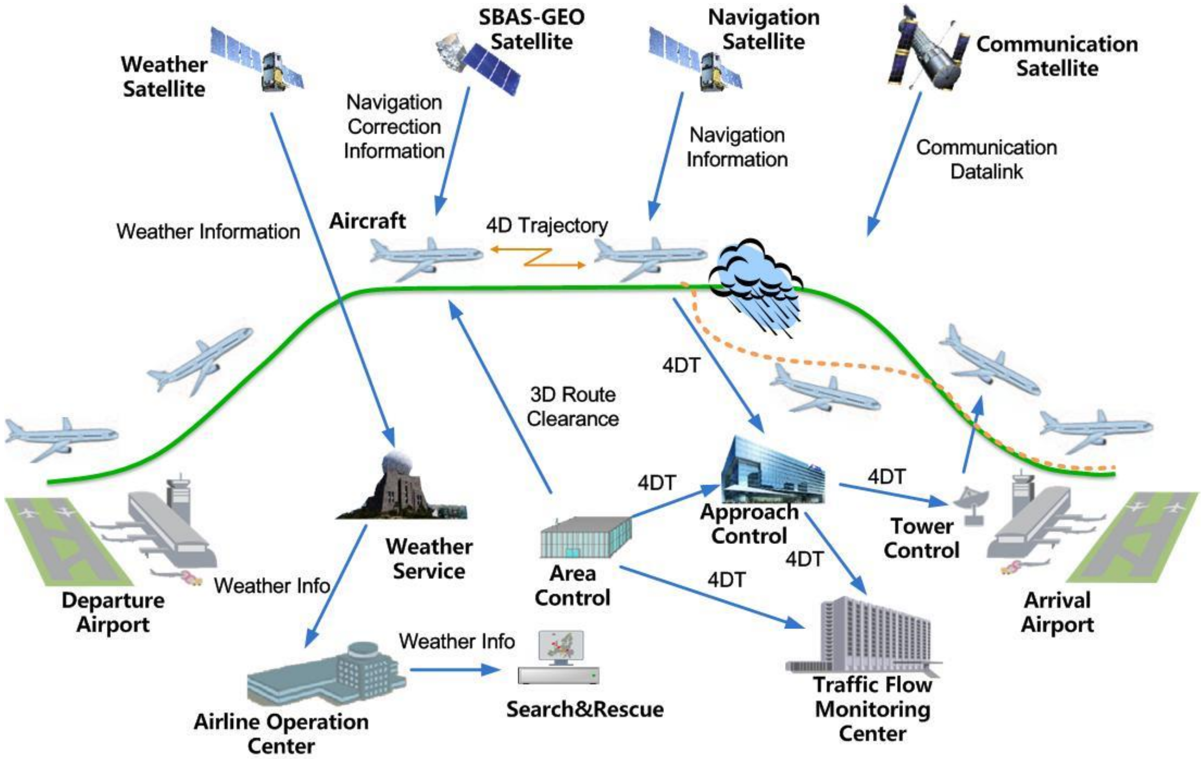

Figure 2 – 4DT-based ATM Typical Operational Scenario

According to above scenario, greener air traffic operation objectives can be identified as 9 flight phases discussed in the previous sector. Stakeholders participating in the whole process are considered as 11 operational nodes: aircraft, national air traffic control center, airport, area control center, approach control center, tower control center, airline operation center, flight information management department, search & secure department, weather service department and national flow monitoring center. There are reliance relationships between each objective and several operational nodes, which represent that the collaboration and coordination of these nodes are required to realize the corresponding objective. (Shown as Figure 3).

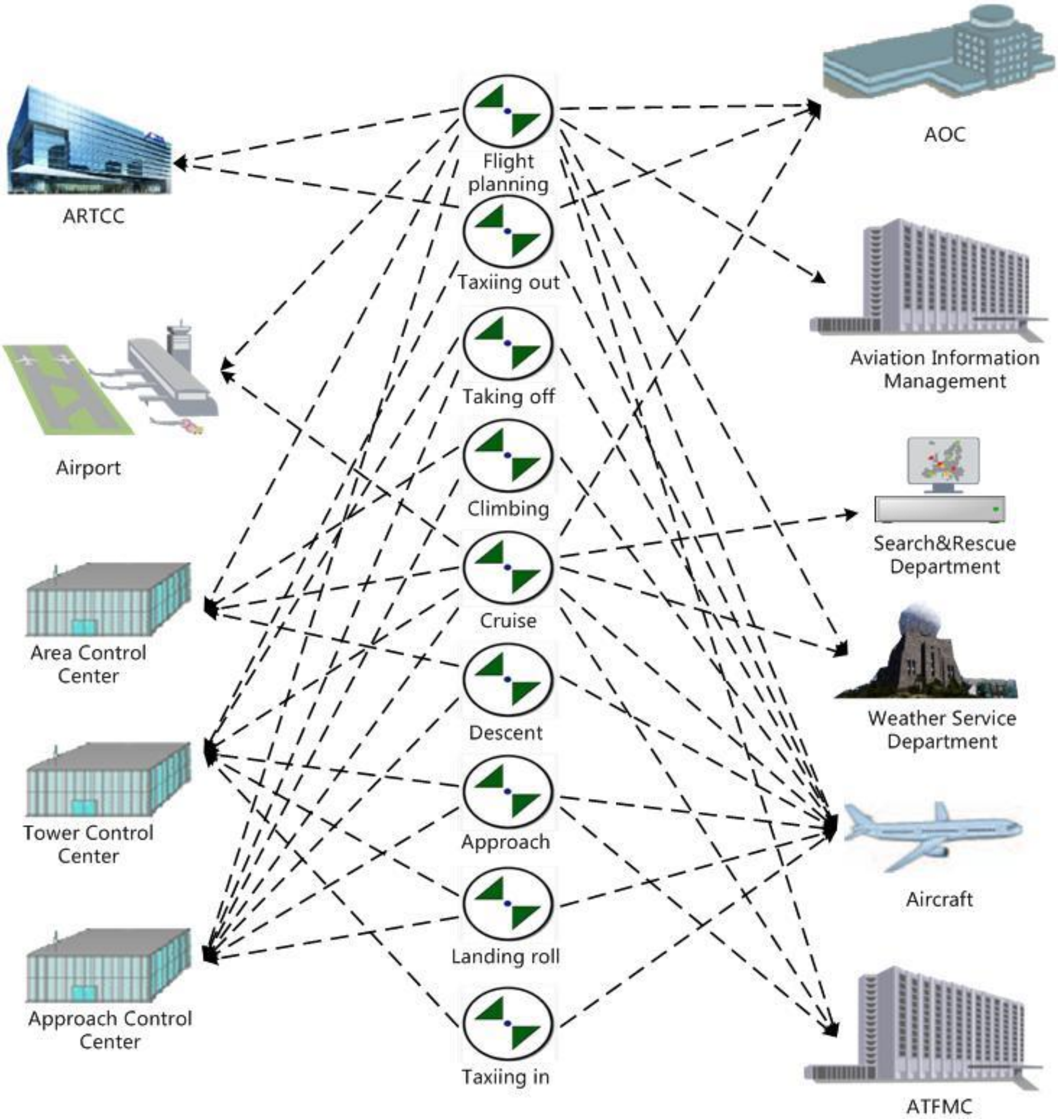

Figure 3 – High-level Operational Concept Diagram

3.1.2 Operational Activity Model

Operational activity model mainly describe a series of activities required to accomplish the operation objectives, which consist of activity name, input/output data flow between activities and information exchange with external environment. Each objective relate to its operational activity model, defining roles and responsibilities of stakeholders in the operation. Taking cruise phase as an example, this model shows the coordination process between aircraft and area control center: 1) Aircraft downlinks the calculated 4D trajectory (including a 3D route and an ETA window) to ground ATC center via ADS-C datalink; 2) ATC shares and negotiates the 4D trajectory with other ATC centers, airports and airlines, and sends the updated trajectory to aircraft via CPDLC datalink; 3) Aircraft evaluate the updated 4D trajectory. If it's feasible, sends confirmation message to ATC, otherwise renegotiate the trajectory with ATC; 4) According to the confirmed 4D trajectory, aircraft adjusts its flying conditions via RTA function in FMS to execute the 4DT-based flight. If the aircraft is unable to fly the planned 4DT due to severe weather and a reroute strategy is required, the FMS calculates a new 4DT and sends reroute request to ATC. Stakeholders come to agreement again through negotiation, and ATC sends reroute clearance to the aircraft.

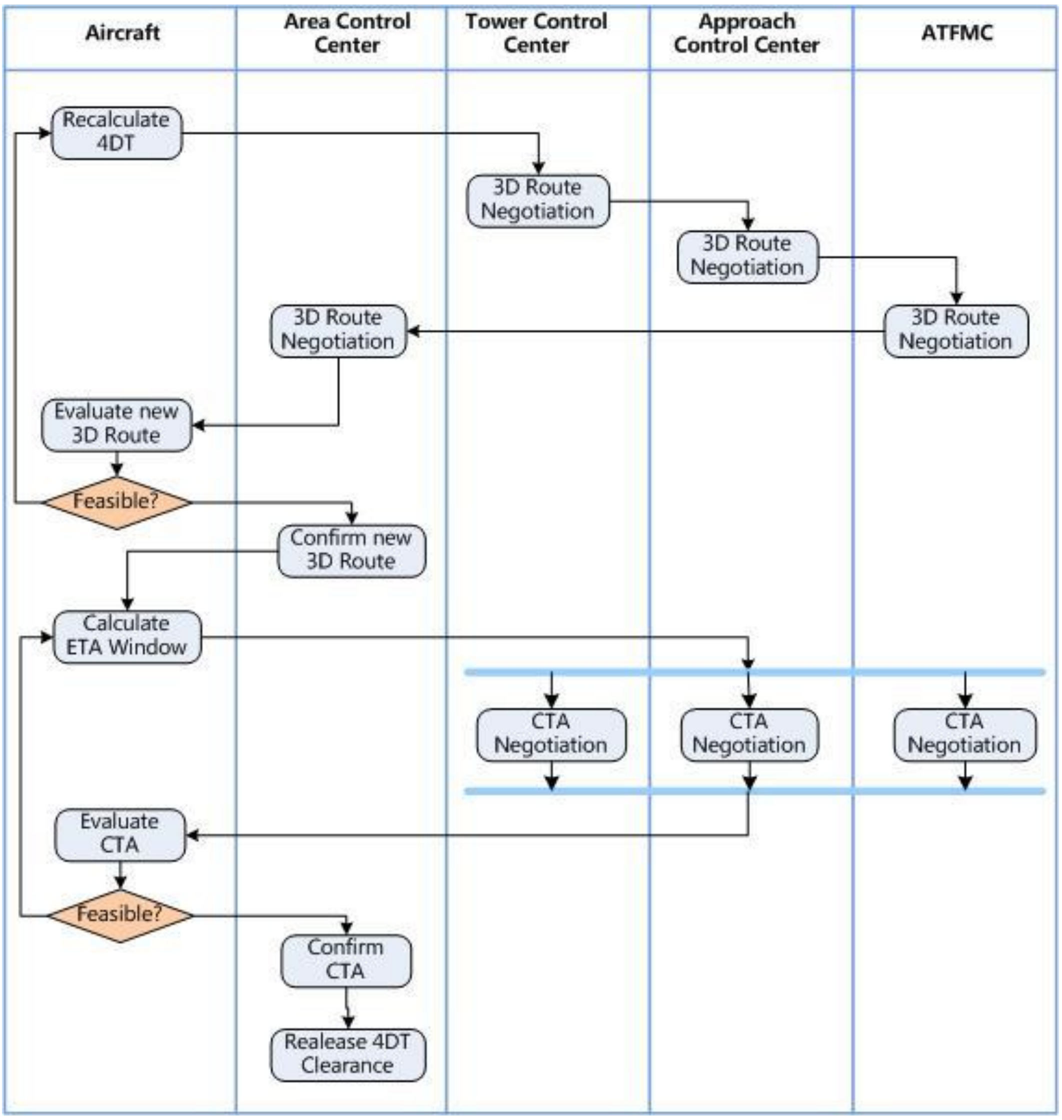

Figure 4 – Operational Activity Model

3.1.3 Operational Event Trace Description

Operational event trace description shows the temporal sequence of events and message transmission in a certain scenario, which is also called sequence diagram. It mainly describes the dynamic characteristics of operational nodes, providing logic port information and operation testing scene. This model relates closely to activity model, and helps analyzing and evaluating activities in perspective of time. Figure 5 demonstrates the operational event trace description diagram corresponding to 4DT negotiation part in cruise phase. Operational event trace description consists of two message type: operation and event, representing the activities of operational nodes and the information exchange among them, respectively.

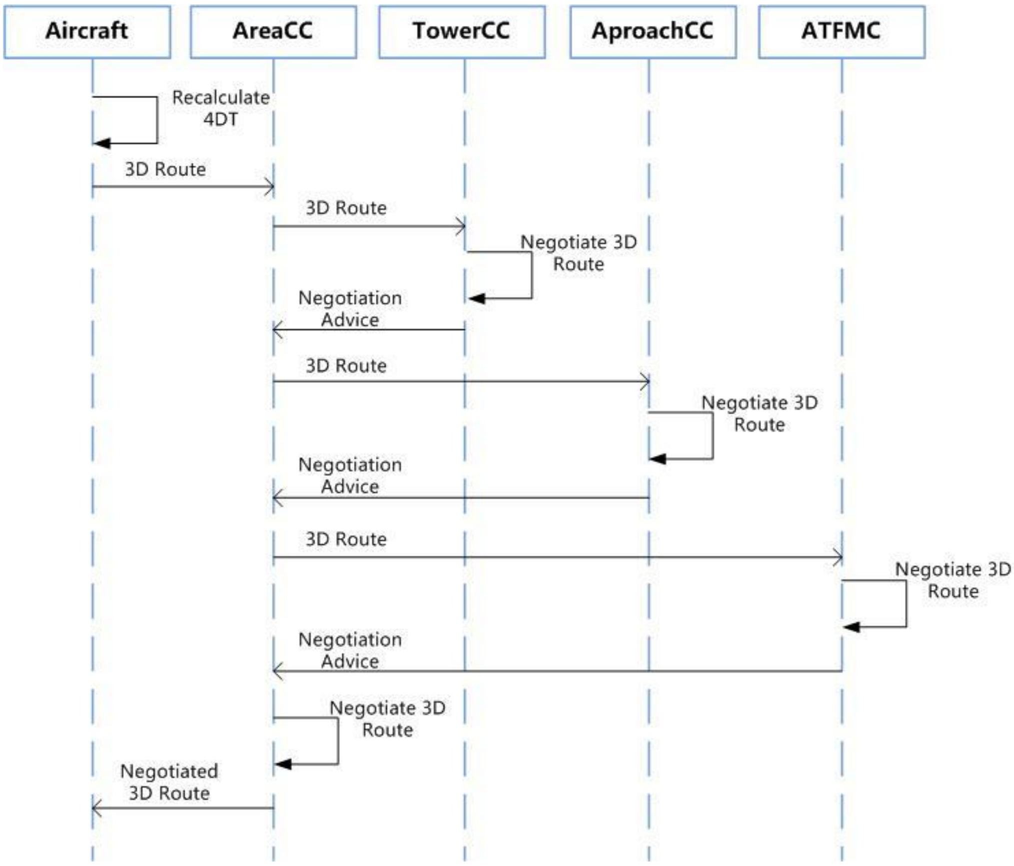

Figure 5 –Operational Event Trace Description

3.1.4 Operational Node Connectivity Description

The component elements of operational node connectivity description are operational nodes and their exchanged information flows. The former can be directly extracted from the high-level operational concept diagram, while the latter have to be decided according to the related operations and events in operational event trace description. In order to simulate the models, it is also required to define ports for crosslinking relationships between the nodes. The simulation of these information exchanges is realized via these ports. Figure 6 shows the operational node connectivity description of 4DT-based ATM operation.

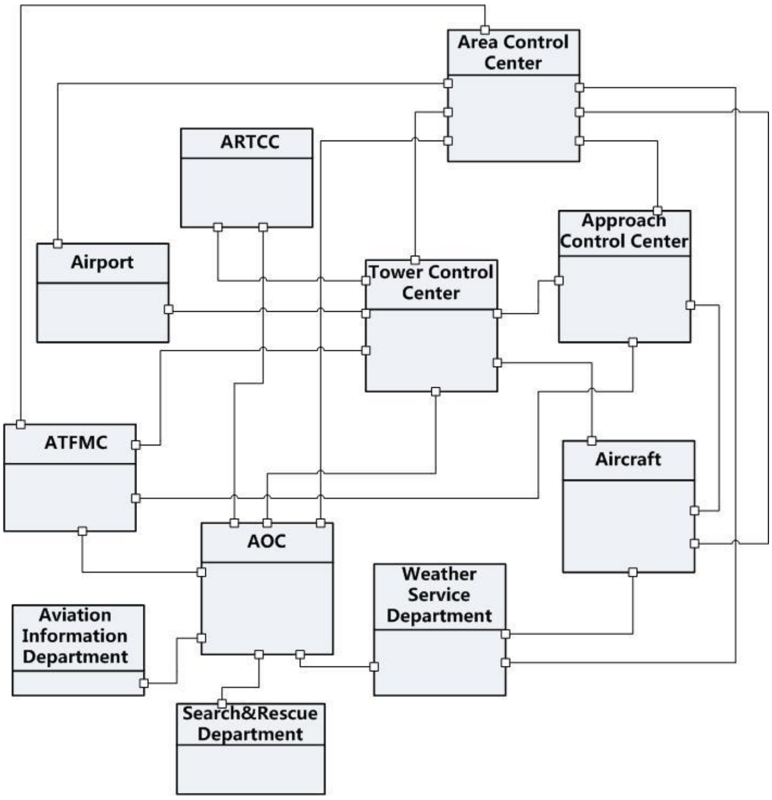

Figure 6 – Operational Node Connectivity Description

3.1.5 Operational State Transition Description

Operational state transition description is the graphic manner used to describe how operational nodes respond to different events, which can be realized in SysML state machine diagrams. The state machine diagram emphasizes system's dynamic behaviors, making it the foundation of executable models. Its fundamental elements include states, transitions, events and operations. Figure 7 shows the state machine diagram of aircraft node in cruise phase. This node has several states like waiting for reroute request, calculating ETA window and executing 4DT. Each state transits to another through event triggering.

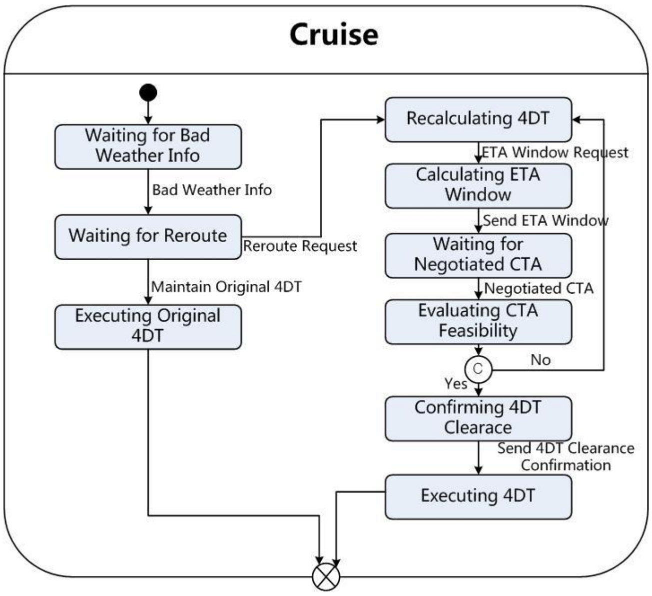

Figure 7 – Operational State Transition Description

3.2 System View Modeling

System View represents the systems, sub-systems, services related to operational requirements, and system functions supporting operational activities. It is introduced to design system capabilities and performance based on agreed standards and demands. System View models consist of system interface description, system functionality description, system event trace description and system state transition description.

3.2.1 System Interface Description

System interface description considers how capability configuration, systems and organizations are established and crosslinked. It describes the system nodes and sub-system nodes required to fulfil operational activities, as well as the ports and interaction relationships among these nodes. It provides the connection of Operational View and System View, as the information exchange and input/output ports among sub-systems can be generated from operational node connectivity description. The sub-systems are identified as the physical entities of the abstract operational nodes in real scenario. For instance, aircraft node corresponds to specific flights with certain flight numbers; airport node can be substantialized as Beijing Capital Airport and Shanghai Pudong Airport; weather service department node can be substantialized as meteo-satellites and weather monitoring centers. Figure 8 shows the system components and interactive relationship of approach control center and tower control center.

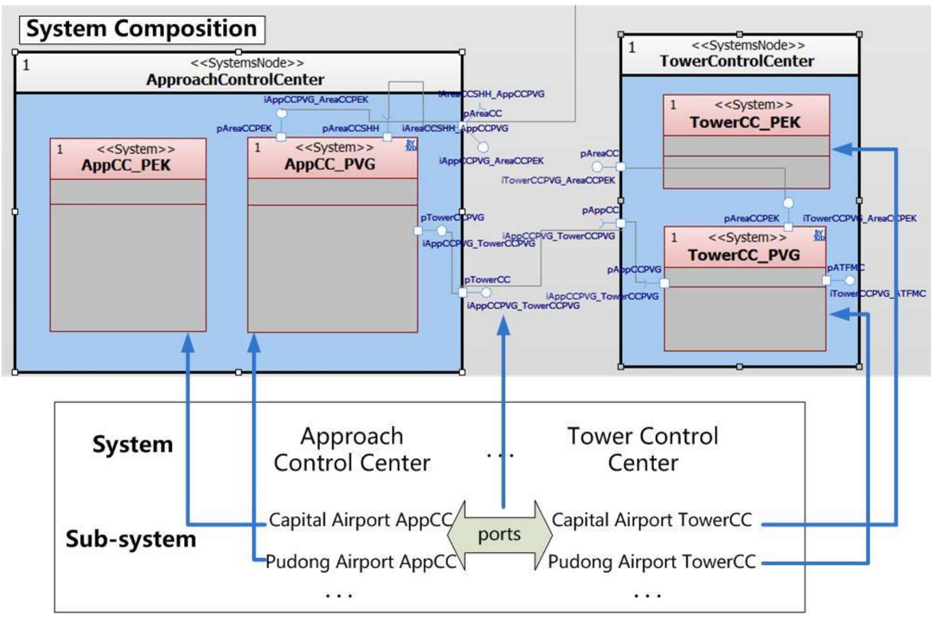

Figure 8 –System Interface Description

3.2.2 System Functionality Description

System functionality description defines system functionality which supports operational activities, which establishes the mapping from operational activities to system interface description and allocation of system functions into sub-systems. These system functions will eventually evolve to system requirements supporting operation, guiding system-level development. Figure 9 demonstrates the system functions supporting activity of acquiring weather information.

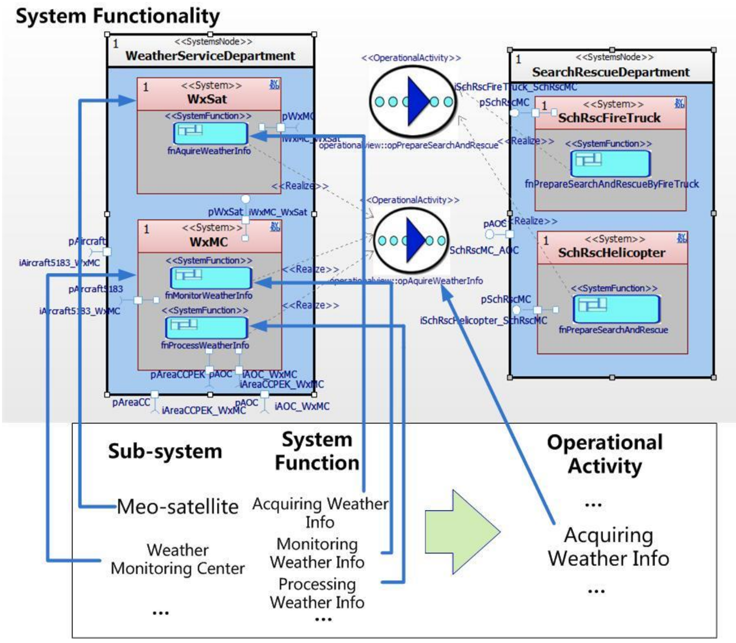

Figure 9 –System Functionality Description

3.2.3 System Event Trace Description & System State Transition Description

System event trace description and system state transition description are similar with their counterparts in Operational View. The former describes system events in the form of sequence diagrams, mainly focusing on system activities and information exchange among sub-system nodes. The latter describes system states and transitions of sub-system nodes in the form of state machine diagrams, generating executable state machine models. The running results of state machine models are important manners to check if the developed system meets the requirements.

4. Visualized simulation realization

Based on developed greener air traffic operational architecture models, this paper designs the framework of visualized simulation realization method using visualized simulation tools, and conducts demonstration and verification of the typical scenario.

4.1 Scenario Simulation Design Scheme

The scenario simulation design scheme includes three elements: data source input, control and CSD (calculation & storage & display). The structural block diagram is shown as Figure 10. The data source input part imports aircraft trajectory data (flight number, longitude, latitude, altitude, speed, etc.), 3D model data and 3D terrain data into database for program calling. VC visual platform is responsible to connect and communicate with Connect module of visualized simulation tools, sending orders and receiving feedback data. CSD element receives control orders sent by VC visual platform, makes calculation with the input data, and conducts simulation and demonstration via integrated information, graphic windows or standard data file output.

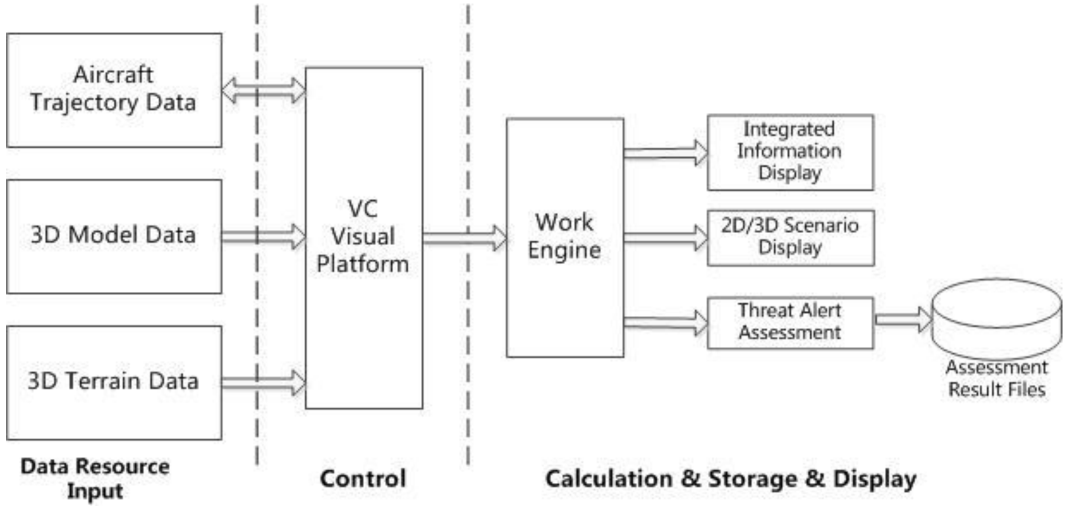

Figure 10 –Scenario Simulation Design Scheme Block Diagram

4.2 Scenario Visualized Simulation Process

The whole airspace in the scenario simulates operation conditions of 96 civil flights. The main simulation object is flight MU5183 from Beijing to Shanghai. The duration of the simulation process is 115 minutes. An emergent thunderstorm is simulated near the flight trajectory of MU5183, forcing it to take reroute strategy. Conflict with flight CES2811 from Nanjing to Beijing is detected when MU5183 is bypassing the dangerous area. Two flights execute conflict-resolution via airborne collision avoidance systems. The simulation tool simulates in detail the negotiation process and related information exchanges of MU5183 with ground control centers and other aircraft.

5. Conclusion

The ATM system supporting greener air traffic operation is a multi-agent and multi-node complex system. In order to cope with the complexity, MBSE method is used to analyze its operational and system architecture. Through the establishment of architecture models and functionality models, ATM system development requirements under greener air traffic operational concept can be effectively obtained. The visualized simulation of typical operational scenario transfers abstract models into precise and intuitional 3D dynamic images and videos, which is helpful for users to verify and validate. From the whole modeling and simulation process of ATM system, the following benefits can be revealed: 1) The decomposition of models helps explore more details in the system; 2) Consistency in different views can be ensured by model-based architecture analysis; 3) In a way architecture analysis is able to predict and analyze emergent behaviors in the system.

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7. Copyright Statement

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